# THE THEORY AND PRACTICE OF RADIOLOGY

## VOLUME THREE

### X-RAY APPARATUS AND TECHNOLOGY

# THE THEORY AND PRACTICE OF RADIOLOGY

## VOLUME THREE

### X-RAY APPARATUS AND TECHNOLOGY

# THE THEORY AND PRACTICE OF RADIOLOGY

## WITH A SYNOPSIS OF RADIOGRAPHY AND RADIOTHERAPY

A TREATISE IN FOUR VOLUMES


BY

BERNARD J. LEGGETT

M.R.C.S., L.R.C.P., A.M.I.E.E.

RADIOLOGIST, EAST LONDON HOSPITAL FOR CHILDREN; STAFF RADIOLOGIST, CITY OF LONDON HOSPITAL FOR DISEASES OF HEART AND LUNGS; RADIOLOGIST, ST. MARK'S HOSPITAL FOR CANCER AND DISEASES OF THE RECTUM; CONSULTANT RADIOLOGIST, ROYAL UNITED HOSPITAL, BATH; LATE VOLONTAR RÖNTGENARTZ, KRANKENHAUS DER JUDISCHEN GEMEINDE, BERLIN; LATE DIAGNOSTIC RADIOLOGIST, MIDDLESEX HOSPITAL, LONDON.


VOLUME THREE

## X-RAY APPARATUS AND TECHNOLOGY


LONDON

CHAPMAN & HALL LTD

11, HENRIETTA STREET, W.C. 2

1928

# AUTHOR'S PREFACE

THE increasing complication of all X-ray apparatus for medical work is making it more and more necessary for medical students, doctors and radiologists to possess a wide knowledge of the physical and electrical principles involved. Existing books have been hitherto divided mainly into two classes—namely, physical or medical—and their study has demanded either a deeper knowledge of physics than can usually be assumed; or a medical knowledge only, which precludes a proper understanding of the principles involved. In the present work the author has endeavoured to provide a sound combination of theory, apparatus and practice. The treatment involves only the simplest mathematics and deals with the Physics of X-Radiation, the Principles of X-Radiation Apparatus, the Measurement of Radiation, the description and efficient working of all types of modern apparatus, and a synopsis of Diagnostic and Therapeutic Radiology, based on a wide and varied experience.

Volume One is in reality a text-book of Electricity and Magnetism, specially written with the requirements of the Radiologist in view. Whilst the treatment follows to some extent that of the more generalised electrical text-book, much of the matter having no direct application to radiology has been omitted; whereas items such as that of the Principles of Electromagnetic Machinery, found only in technological electrical books, have been introduced. The book was not written primarily to cover the requirements of any special examination, as it was in preparation before such came into existence. It has, however, been extended to cover the scope of existing examinations. Acknowledgment is made to the Council of the Society of Radiographers for permission to include questions set at their examinations. The author has also added a number of questions based on typical problems, set for the Diploma in Medical Radiology and Electrotherapy, now granted by Cambridge, Liverpool and Edinburgh Universities.

Volume Two is intended to give the reader a general review of the specialised physics of X-radiation. To ensure a knowledge of fundamentals, an outline of the general properties of radiation has been introduced in its first chapter. X-ray Physics provide a most fascinating study, but very few comprehensive elementary books exist dealing with this subject; and none, as far as the author is aware, specially written from the point of view of the medical applications. The purely physical book, such as that of Sommerfeld, is not suitable for medical readers,

and much of the information has hitherto only been obtainable from scattered original papers, entailing considerable research.

Volume Three is concerned entirely with the apparatus of Practical Radiology, and, after an account of High Vacua Production, what is believed to be the most comprehensive treatment on the X-ray Tube is given. This is followed by a chapter in which, for the first time, the fundamental considerations in the design of X-ray High-tension Transformers is given, a subject upon which little but popular details have hitherto been written.

No apology is made for the inclusion of a very large number of manufacturers' blocks in this section, for it must be recollected that invariably the medical radiologist purchases his apparatus, and hence quite 99·5 per cent. of his requirements are supplied by manufacturers. Full use has therefore been made of the many excellent blocks loaned by companies. No preference has been given to any particular firm ; in fact, practically every X-ray manufacturing company of importance throughout the world has been approached for the loan of blocks, where the subject of the block is original, or displays some technical point. The generous response, as shown by the illustrations, is gratefully acknowledged and the source is indicated under most of the figures.

It is hoped that the more detailed considerations of X-ray apparatus on the part of the medical reader will result in a demand for apparatus from the manufacturers of ever increasing utility.

The author wishes to express his thanks to the following specialists who have been kind enough to read and criticise the various chapters :

Professor Gaede for the chapter on High Vacua Production ; Dr. Bouwers, of Messrs. Philips Lamps, Ltd., and Dr. Daumann, of Messrs. Müller, of Hamburg, for the two chapters on X-ray Tubes ; Mr. S. Austen Stigant (Manager of the Transformer Department, Messrs. Johnson and Phillips) for the chapter on Transformers ; Mr. R. S. Wright, for the chapter on the Induction Coil ; Mr. G. Dean, for the chapter on Couches and Screening Stands, and for the chapter on Accessory Apparatus. He also wishes to thank Dr. W. Morrison for permission to include a description of the Royal Infirmary, Edinburgh, Professor P. M. Hickey for photographs and details of his Ann Arbour installation, and particularly Dr. L. R. Sante for his generous response to the request for particulars of his St. Louis installation.

For criticism and much help of the three volumes thanks must be expressed to Dr. G. H. Cordiner from the medical side, and Mr. J. Haggard, B.Sc., from the physical side. Lastly, the author would thank his publishers for their courage in giving a contract for this book with only

the scheme outlined and before it was written ; and Mr. John L. Bale of that firm for much assistance during its preparation. It cannot be expected, in a work of this magnitude, that no errors occur, and the Author will be grateful to have these pointed out ; or omissions indicated.

A further volume will deal with the diagnostic and therapeutic applications of X-radiation.

It is hoped that the work will be of value to all doctors and radiologists, and will serve as a comprehensive text-book for medical students desiring to cover the scope of any radiological examination.

B. J. L.

EAST LONDON HOSPITAL FOR CHILDREN,
*October*, 1927.

# CONTENTS



## APPENDICES

# ABBREVIATED REFERENCES TO JOURNALS

| | |
|---|---|
| Acta Rad. | Acta Radiologica (Sweden). |
| Amer. Jour. of Rönt. | American Journal of Röntgenology. |
| Ann. der Phy. | Annalen der Physik. |
| Arch. Elect. Med. | Archives d'Électricité Médicale. |
| Assoc. Amer. Phys. | Association of American Physicists. |
| Ber. der phy. med. Ges. der Wurzburg | Bericht der physikalischen medischen Gesellschaft der Wurzberg. |
| Ber. der phy. med. Ges. der Erlangen | Bericht der physikalischen medischen Gesellschaft der Erlangen. |
| Brit. Jour. Rad. | The British Journal of Radiology. |
| Bull. Soc. Rad. | Bulletin de la Société de Radiologie. |
| Comptes Rendus | Comptes Rendus (France). |
| Electrical Communications. Western Elect. Co. | Electrical Communications of the Western Electrical Company (U.S.A.). |
| Electrician | Electrician (London). |
| Engineering | Engineering (London). |
| Elek. tech. Zeits. | Elektrotechnishen Zeitschrift. |
| Exam. Soc. of Rad. | Examination of The Society of Radiographers. |
| Fort. a. d. Geb. der Rönt. | Fortschritte auf dem Gebiete der Röntgenstrahlen. |
| Gen. Elect. Rev. | The General Electric Review (U.S.A.). |
| Jahr. der draht. Tele. | Jahrbuch der drahtlosen Telegraphie. |
| Jour. Amer. Inst. of Elect. Engs. | The Journal of the American Institute of Electrical Engineers. |
| Jour. de Phy. | Journal de Physique (France). |
| Jour. Inst. Elect. Engs. | The Journal of the Institute of Electrical Engineers (London). |
| Jour. of Indust. and Chem. Eng. | Journal of Industrial and Chemical Engineering (U.S.A.). |
| Jour. Opt. Soc. Amer. | The Journal of the Optical Society of America. |
| Jour. Rönt. Soc. | The Journal of the Röntgen Society (London). |
| Nature | Nature (London). |
| Phil. Mag. | The Philosophical Magazine (Cambridge). |
| Proc. Am. Phys. Soc. | The Proceedings of the American Physical Society. |
| Proc. Camb. Phil. Soc. | The Proceedings of the Cambridge Philosophical Society. |
| Proc. Phys. Soc. | The Proceedings of the Physical Society (London). |
| Proc. Roy. Soc. | The Proceedings of the Royal Society (London). |
| Phys. Rev. | The Physical Review (U.S.A.). |
| Phys. Zeits. | Physikalischen Zeitschrift. |
| Rev. d'Optique | La Révue d'Optique. |
| Rev. Gen. d'Élect. | La Révue Générale d'Électricité. |
| Verh. der deut. phys. Ges. | Die Verhandlungen der deutschen physikalischen Gesellschaft. |
| Zeits. für Elekt. | Zeitschrift für Elektrotechnik. |
| Zeits. f. Phys. | Zeitschrift für Physik. |
| Zeits. f. phys. Chem. | Zeitschrift für physikalischen Chemie. |
| Zeit. f. tech. Phys. | Zeitschrift für technischen Physik. |

# CONTENTS OF COMPLETE WORK

## VOLUME I

### ELECTRICAL THEORY APPLIED TO RADIOLOGY



## VOLUME II

### THE PHYSICS AND MEASUREMENT OF X-RADIATION

## CONTENTS OF COMPLETE WORK

### VOLUME III

### X-RAY APPARATUS AND TECHNOLOGY



### VOLUME IV

### DIAGNOSTIC RADIOLOGY



### THERAPEUTIC RADIOLOGY

# VOLUME III

# CHAPTER I

## THE PRODUCTION AND MEASUREMENT OF HIGH VACUA

A KNOWLEDGE of the methods by which high vacua may be obtained should be of general use to the medical radiologist. For one thing it enables him to see how simply and how cheaply high vacua can be obtained. Further it is by no means improbable that, in the near future, the larger, clinical X-ray laboratories will evacuate the X-ray tube *in situ*, an operation carried out daily in many physical research laboratories and by no means impossible in the clinical laboratory. A vacuum pump can be easily constructed at the cost of a few pounds, and the exhaustion of tubes by a skilful mechanician is simple, particularly if, as foreshadowed, the present glass bulb of the X-ray tube is replaced by a metal container. It is therefore felt that a brief review of the methods used to obtain and to measure the pressure of high vacua is warranted.*

High-vacua production is a branch of applied physics which has made the greatest strides during the past dozen years.

The obtainance of high vacua is of industrial importance, firstly in the large-scale mass production of the ordinary electric light bulb, in the production of thermionic valves and rectifiers for telegraphic and telephonic purposes, and to a less extent in the production of X-ray tubes. In the industrial production of electric light bulbs the production and exhaustion of the bulbs is now largely automatic, and, in America, such automatic production has been applied to the manufacture of X-ray tubes.

High-vacua technology has been chiefly developed in Germany and in America. Foremost amongst those concerned in high-vacua technology must be placed the name of Gaede, and in its measurement the name of Knudsen. Mention should also be made of Dushman and Coolidge in America, and of Holweck and Dunoyer in France.

Methods of obtaining high vacua may be classified as follows ;

(1) *Mechanical Pump Processes.*

(*a*) Piston pumps.
(*b*) Töpler and Sprengel pumps.
(*c*) Rotary mercury pumps.
(*d*) Rotary oil pumps.

* The description of pumping apparatus has already been demanded in a recent D.M.R.E. Examination of Cambridge.

(2) Pumps depending upon the viscosity of gases, so-called m
cular pumps and injector pumps.

(3) Mercury vapour pumps.

(*a*) Gaede diffusion pumps.

(*b*) Langmuir condensation pump.

(4) Processes dependent upon gaseous occlusion or chemical action;

(*a*) absorption by charcoal, or by platinum black;

(*b*) clean up by chemical reactions, *i.e.*, the use of phosphor magnesium, etc;

(*c*) clean up by ionisation.

*Speed of Exhaustion.*—In high-vacua technology it is common speak of the speed of a pump, *i.e.*, the time necessary to allow exhaustion from a given pressure to a lower given pressure.

If S is the speed of the pump it can be shown;

$$S = \frac{V}{t_2 - t_1} \log \frac{(p_1 - p_o)}{(p_2 - p_o)}$$

where V = volume to be exhausted.

$p_1$= original pressure at time $t_1$

$p_2$= final pressure at time $t_2$

$p_o$= lowest obtainable pressure with the particular pump.

If in this equation we put $t_2 - t_1$ = one second and $\frac{p_2}{p_1}$ $\frac{p_o}{p_o}$ then S = V, *i.e.*, the speed of the pump is the volume of gas evacuated one second from an original pressure of $p_1$, to a final pressure $p_2$ which related as; $\frac{p_2}{p_1} = \frac{1}{e} = 63 \cdot 2$ per cent., if $p_o$ the pressure limit is negligibl

*Units of Pressure.*—At pressures about or above atmospheric pressu it is common to denote gas pressures in terms of atmospheres, or in ter of the force exerted per unit area. Approximately 750 mm. of mercu at 0° C. has a pressure of $10^6$ dynes per square centimetre. This val is termed the *megabar*.

In high-vacua technology a new unit is introduced, namely the *b* (or barye), where 1 bar equals a gas pressure of 1 dyne per squa centimetre, and corresponds to a pressure equal to that of ·0075 mm. mercury.

The following relations exist;

1 mm. of mercury = 1,342 bars.

1 $\mu$ ($\frac{1}{1000}$ mm.) of mercury = 1·342 bars.

750 mm. of mercury = 1,006,500 bars.

In high-vacua technology fractions of a bar as $\frac{1}{10000}$ are common, f example, the ordinary gas or ionic tube has a pressure of about 1 ba and the Coolidge electron tube of about ·06 bar.

Pumps depending upon the viscosity of gases, so-called mole-
umps and injector pumps.
Mercury vapour pumps.
(*a*) Gaede diffusion pumps.
(*b*) Langmuir condensation pump.
Processes dependent upon gaseous occlusion or chemical re-

(*a*) absorption by charcoal, or by platinum black ;
(*b*) clean up by chemical reactions, *i.e.*, the use of phosphorus, magnesium, etc ;
(*c*) clean up by ionisation.

*d of Exhaustion.*—In high-vacua technology it is common to f the speed of a pump, *i.e.*, the time necessary to allow the ion from a given pressure to a lower given pressure.
is the speed of the pump it can be shown ;

$$S = \frac{V}{t_2 - t_1} \log \frac{(p_1 - p_o)}{(p_2 - p_o)}$$

= volume to be exhausted.
$_1$= original pressure at time $t_1$
$_2$= final pressure at time $t_2$
$_o$= lowest obtainable pressure with the particular pump.

this equation we put $t_2 - t_1 =$ one second and $\frac{p_2}{p_1} \quad \frac{p_o}{p_o} \quad \frac{1}{e}$,
= V, *i.e.*, the speed of the pump is the volume of gas evacuated in nd from an original pressure of $p_1$, to a final pressure $p_2$ which is s ; $\frac{p_2}{p_1} = \frac{1}{e} = 63{\cdot}2$ per cent., if $p_o$ the pressure limit is negligible.

*of Pressure.*—At pressures about or above atmospheric pressure mon to denote gas pressures in terms of atmospheres, or in terms rce exerted per unit area. Approximately 750 mm. of mercury has a pressure of $10^6$ dynes per square centimetre. This value l the *megabar.*

gh-vacua technology a new unit is introduced, namely the *bar* e), where 1 bar equals a gas pressure of 1 dyne per square re, and corresponds to a pressure equal to that of ·0075 mm. of

following relations exist ;

| | | |
|---|---|---|
| 1 mm. of mercury | = | 1,342 bars. |
| 1 $\mu$ ($\frac{1}{1000}$ mm.) of mercury | = | 1·342 bars. |
| 750 mm. of mercury | = | 1,006,500 bars. |

vacua technology fractions of a bar as $\frac{1}{10000}$ are common, for , the ordinary gas or ionic tube has a pressure of about 1 bar, Coolidge electron tube of about ·06 bar.

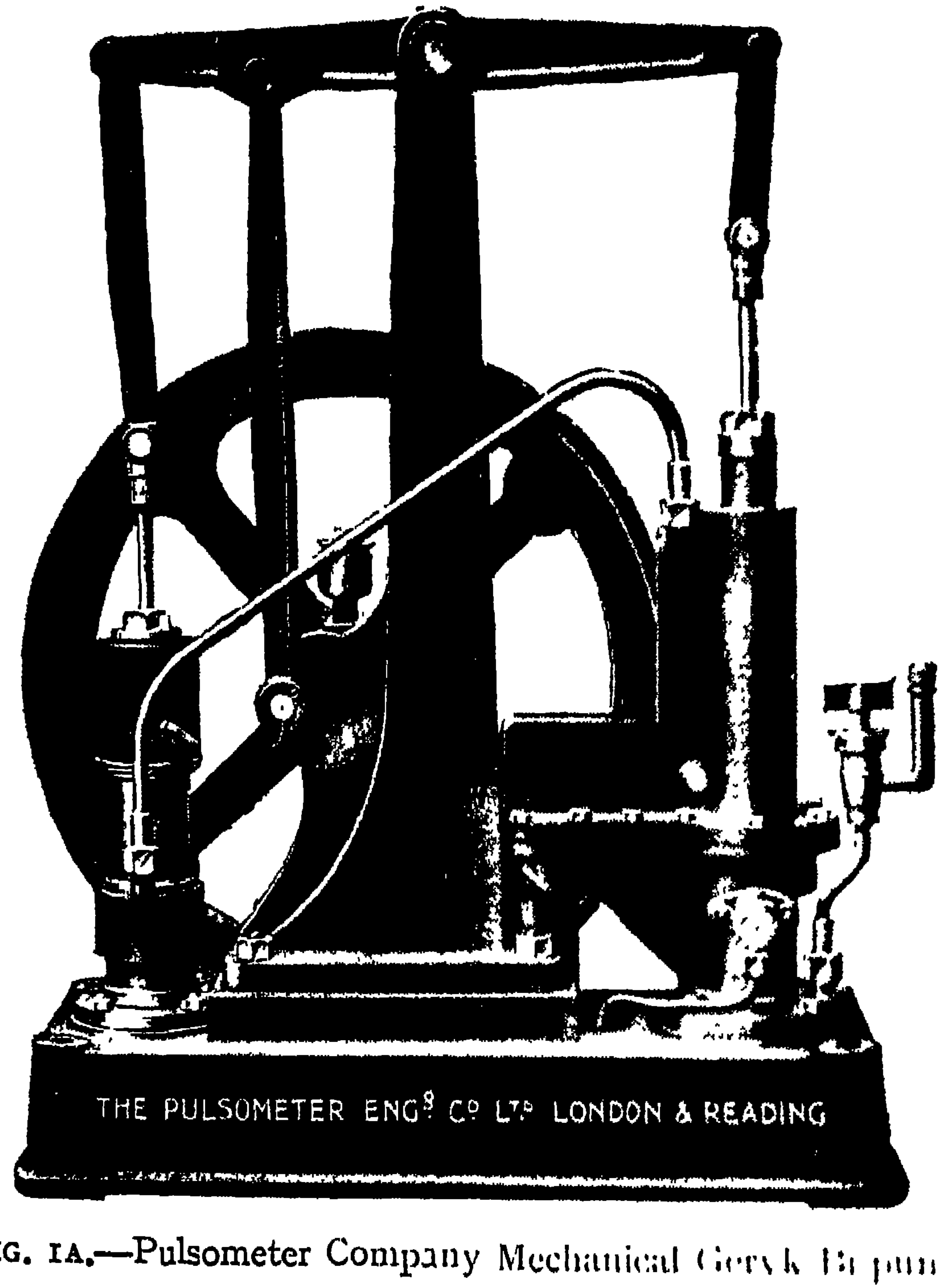



FIG. 1A.—Pulsometer Company Mechanical Geryk B pump

## MECHANICAL PUMPS

*Piston Pumps.*—In modern high-vacua technology the piston pumps are of very little importance. They are the oldest type of pump and date from the Otto von Guericke pump of the seventeenth century, later improved by Boyle, Hawksbee and by Smeaton

Examples of such pumps will be found described in elementary text-books of physics and are to be found in many physical teaching laboratories, for the purpose of quickly obtaining rough vacua.

A modern bi-pump form made by The Pulsometer Engineering Co., Ltd., is shown in Fig. 1A, and sectionally in Fig. 1B. Its action is

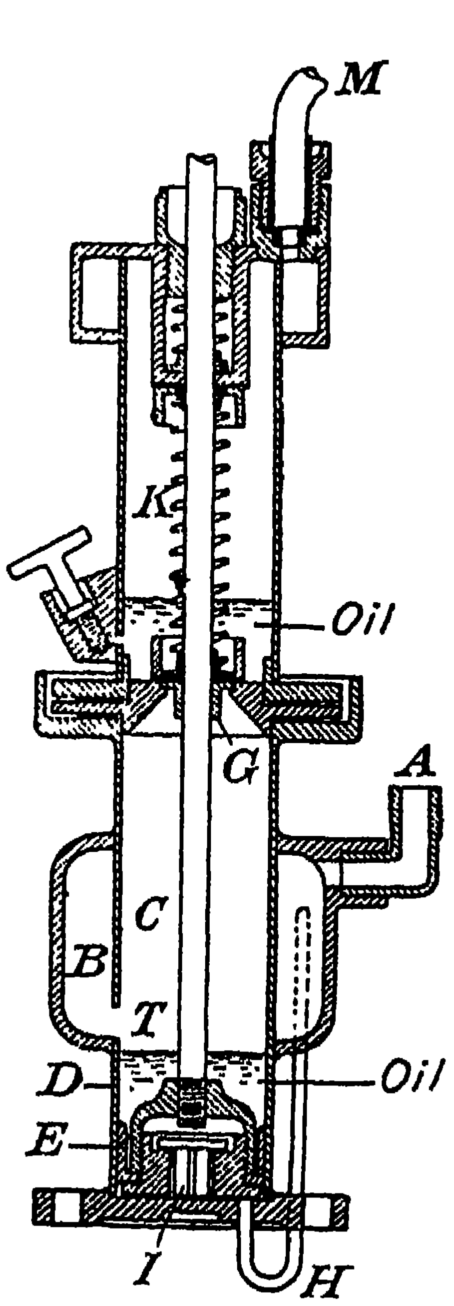



FIG. 1B.—Section of Geryk Pulsometer Pump.

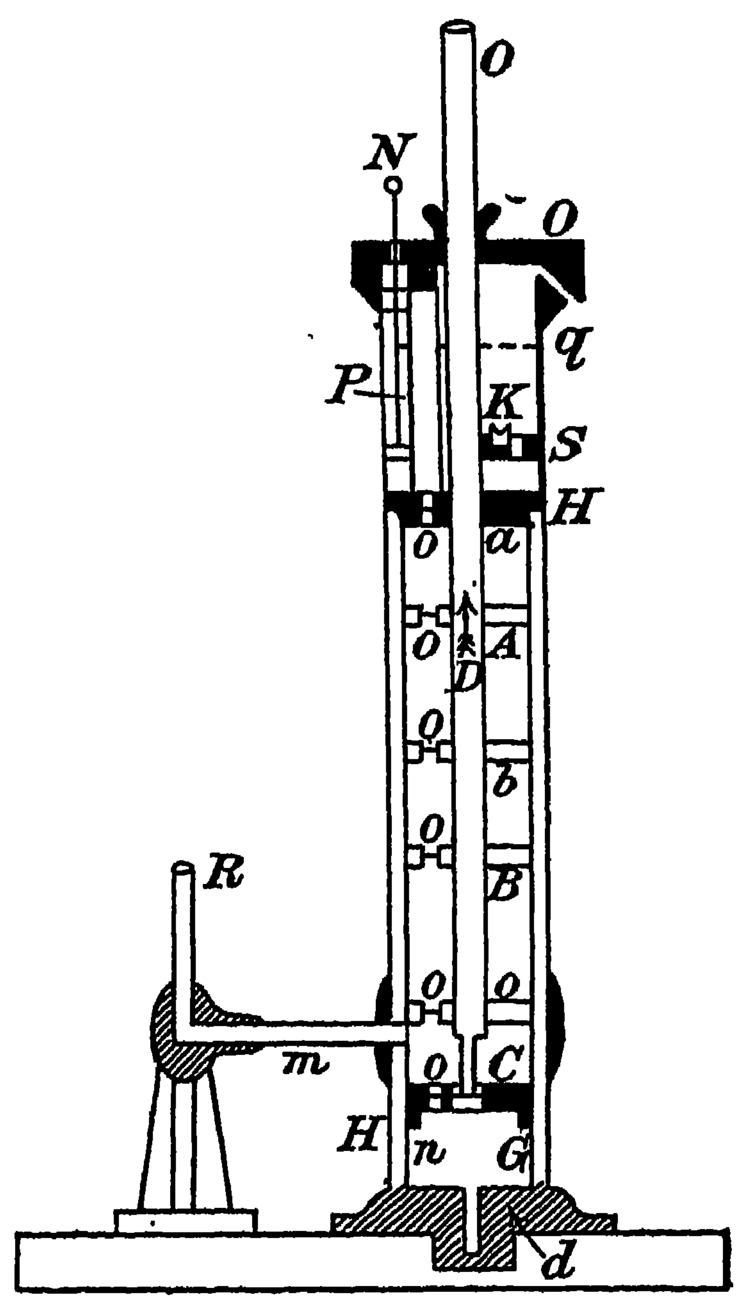



FIG. 2.—Gaede Three-stage Pump.

that its piston when upon its up stroke cuts off the air port B connected *viâ* A, with the vessel to be exhausted. As the up stroke is continued the pressure upon the valve G increases until it is able to lift against the spring K, so that the air is forced out of the pump *viâ* M. On the down stroke re-entry of air is prevented by re-closure of the valve G under oil.

By modern standards the degree of vacua obtainable by this type of pump is not very considerable, being according to Dushman, ·25 mm. of mercury, or 350 bars.

The manufacturers state however; "A vacuum of a hundred-thousandth, and even a millionth of a millimetre has been obtained

upon a commercial McLeod gauge, but with these high vacua, impracticable to give any exact figures. The 'Geryk' pumps exhaust to absolute pressures (vacuum) far below the vapour te of the oil, and the high efficiency is due to the almost complete e nation of this vapour tension during the working of the pump."

Gaede considerably improved this type of pump, and has stated a vacuum of ·00005 mm. of mercury, or ·067 bar, is then possible of at ment. The Gaede piston pump consists essentially of three pump series formed by the pistons A, B, and C of Fig. 2. Upon the down st air in *n*, in communication with the vessel to be exhausted *viâ* I forced in order *viâ* valves *o* to escape finally *viâ* K, which is cov by oil, into the atmosphere *viâ* *q*. The emulsion of air, water oil which collects above K is periodically drawn off by a syr *viâ* N.

## MECHANICAL MERCURY PUMPS

This type of pump is exemplified by those of Sprengel and of Töp They have the virtue of extreme simplicity and can be constructed

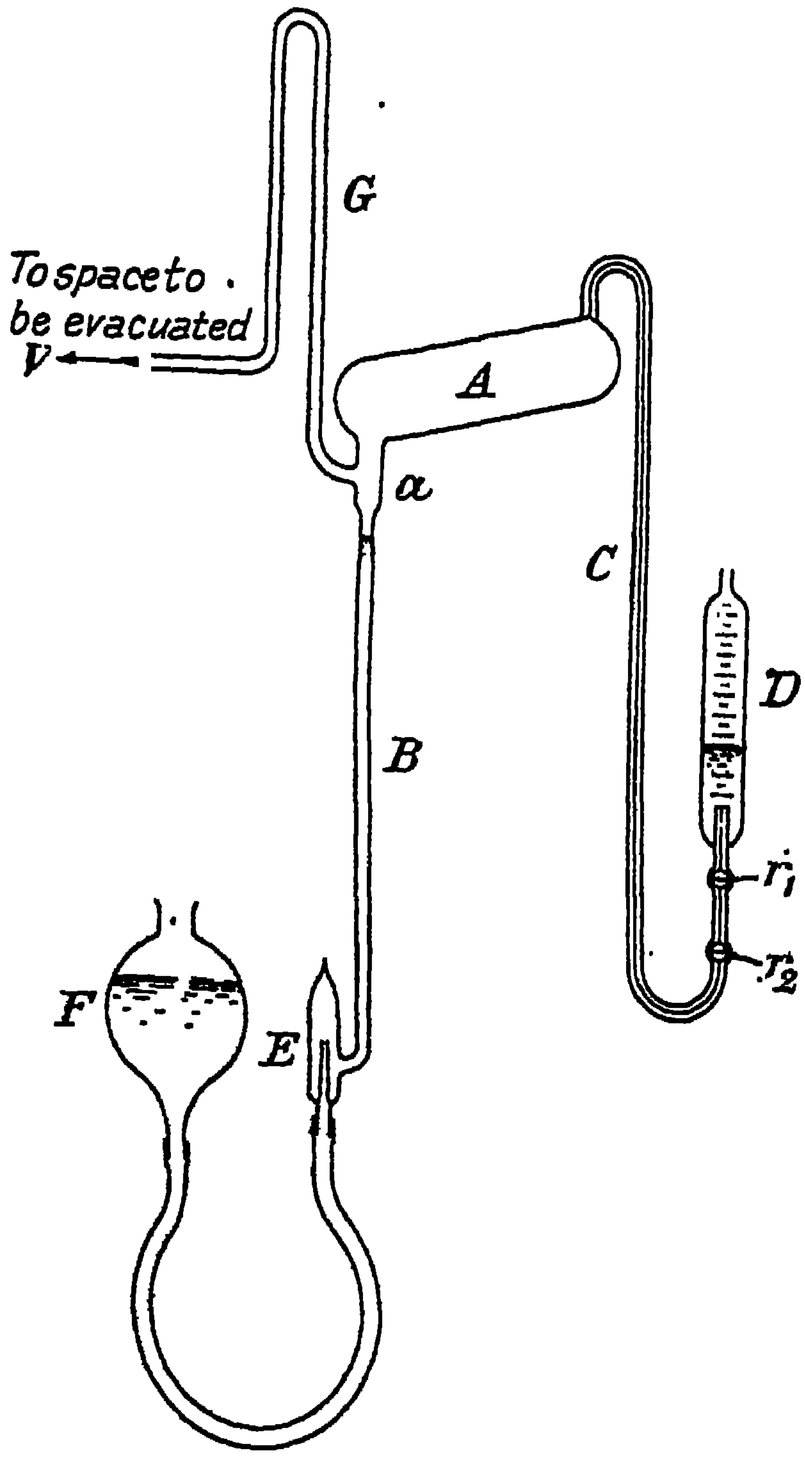



Fig. 3.—Geissler Pump.

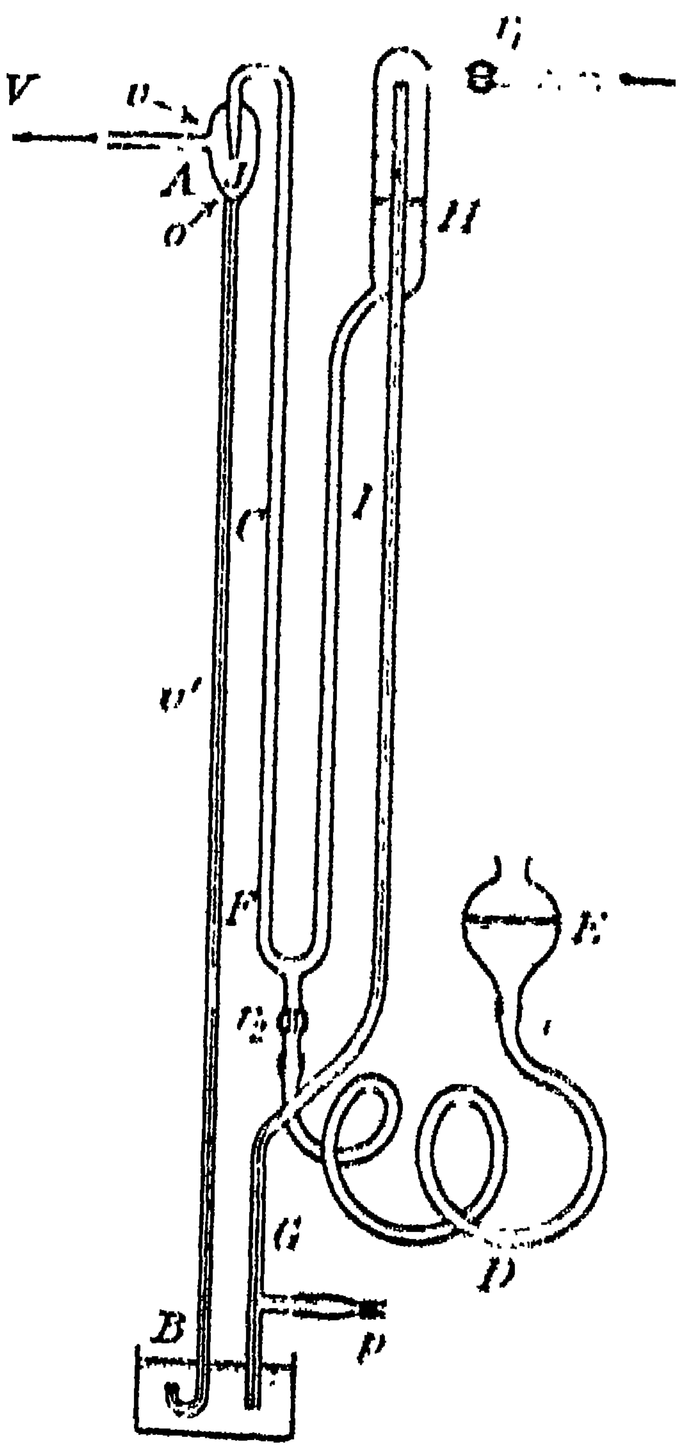



Fig. 4.—Sprengel Pump.

the amateur glass blower. They allow a moderately high degree of vacuum (about ·1 bar) to be obtained, but suffer from the defect that they are not easily operated automatically. As usually operated by hand, they are extremely slow and therefore unable to compete with the more modern mechanical pumps, although in the early days of X-radiology they were much used to exhaust the low-vacua tubes of this period.

*Geissler Pump* (1862).—This is shown in Fig. 3. A mercury container F is originally raised until the vessel A is full of mercury, the space

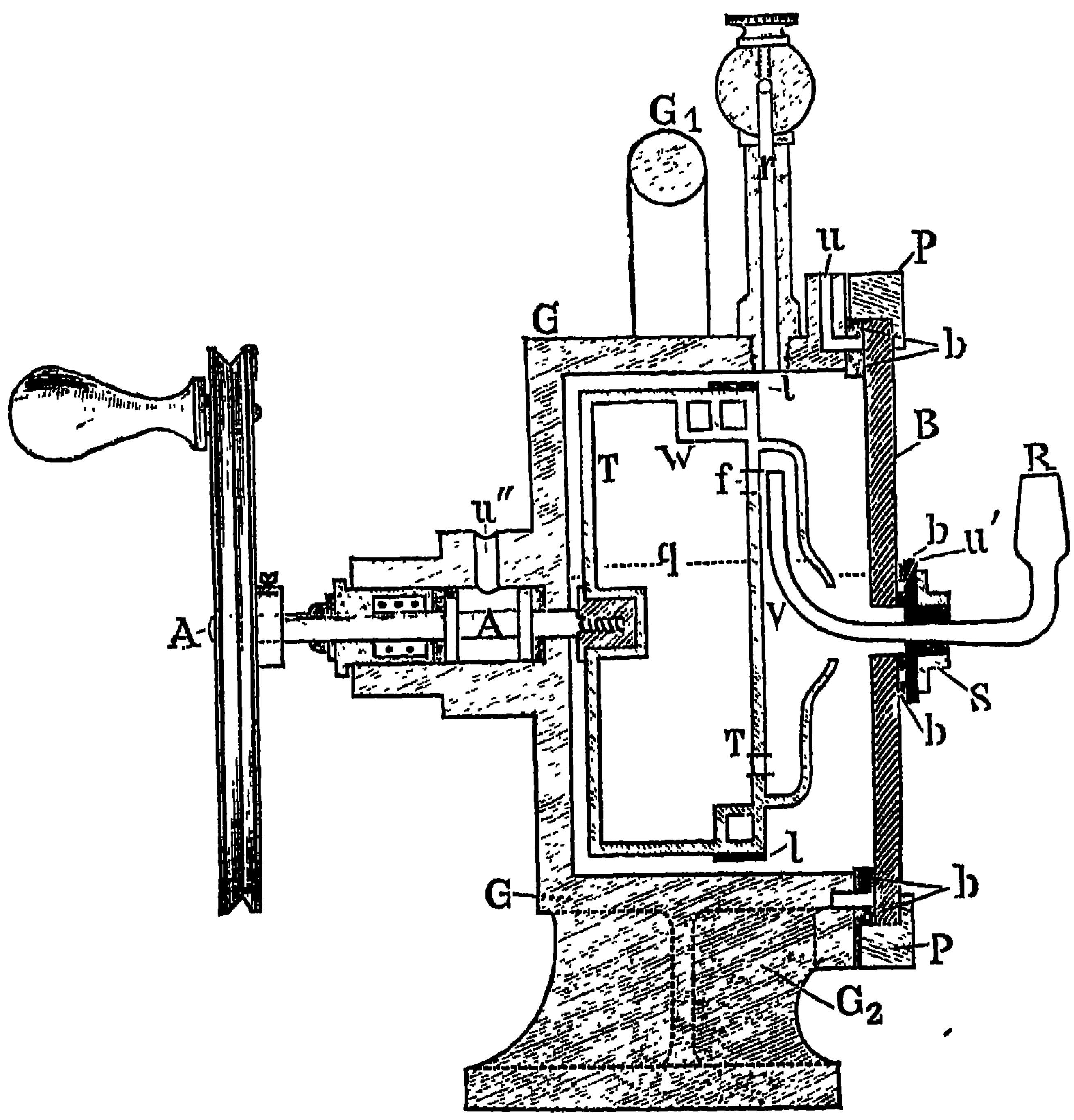



FIG. 5A.—Gaede Rotary Mercury Pump.

to be evacuated being cut off by *a*, and communication with the atmosphere being prevented by the trap D. On lowering the container F the mercury falls from A, which is filled by gas *viâ* G, with consequent lowering of pressure in the space to be evacuated.

When F is again raised the volume of gas in A is cut off at *a* and forced *viâ* D. The sequence of operations results in a repeated equalisation of pressure in A and V (the vessel to be exhausted) at the expense of the gas in V and the repeated evacuation of this space.

A complete cycle usually takes about four minutes, and to evacuate to a pressure of ·01 bar requires about 100 repetitions of the opera-

tion, dependent upon the relative proportions of pump and vessel t(
evacuated.

*The Sprengel Pump.*—This is equally simple in operation, and lc
itself somewhat more easily to automatic operation.

Essentially the action is due to the fall of drops of mercury with
container E (Fig. 4) which drops *viâ* a jet J. On falling to the ori
O it cuts off the volume $v'$ of the tube C (over 1 m. in height) fr
the total volume $V + v + v'$. The fall of the drop of mercury remc
this volume of gas $v'$ from the total volume.

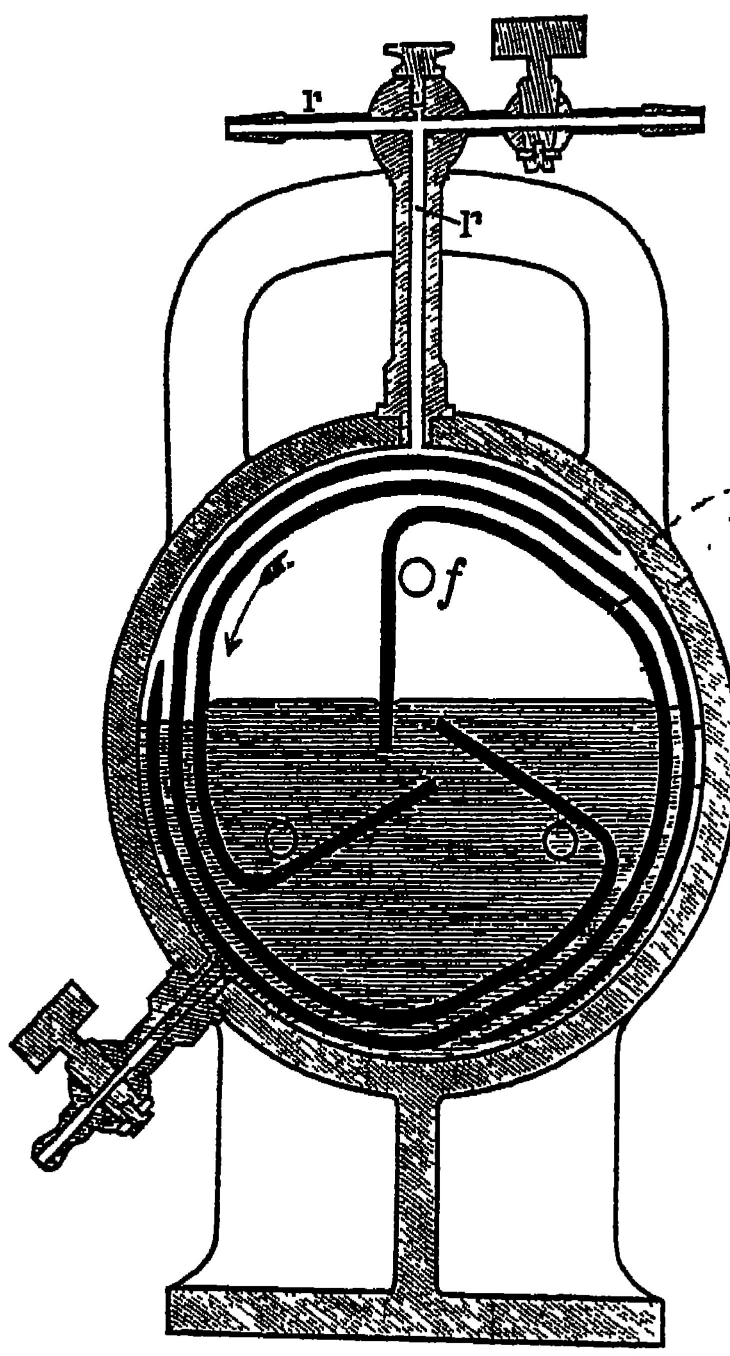



FIG. 5B.—Gaede Rotary Mercury Pump.

The sequence of the mercury dr
is very rapid. In consequence
total volume, $V + v$, is rapidly lowe
in pressure by removal of gas trap
by the mercury drops.

Many modifications of this pu
exist. The lower limit of pressur
that of the vapour pressure of m
cury itself at normal temperatu
and this amounts to 1 or 2 bars.
interposing a liquid air trap (*q.v.*) s
lower pressures can be obtained, ev
as low as ·002 bar.

*The Rotary Mercury Pump.* T
pump, produced by Gaede in 19
may be considered as a mechani
Geissler pump.

An iron casing G (Figs. 5A and 5
is more than half filled to a leve
with mercury and is connected at
to a fore vacuum. Within this casi
is a porcelain rotor T, actuated by
motor or the hand wheel A *viâ* gea
This porcelain rotor has three sy
metrically arranged chambers which are formed by the partitions sho
by heavy lines in Fig. 5B, each chamber communicating with a comm
chamber by means of the openings $f$. These openings are only pot
when the appertaining chamber is above the mercury, when by means
R, they are in connection with the vessel to be exhausted.

If the rotor is given motion in an anti-clockwise direction t
volume of any partitioned space is first put into communication wi
the vessel *viâ* R and $f$, whilst connection to the fore vacuum at $l$
prevented by the long partition being beneath the mercury lev
Further rotation then causes $f$ to be closed by mercury, so that the
cannot pass back to the vacuum chamber, but, by further rotatic

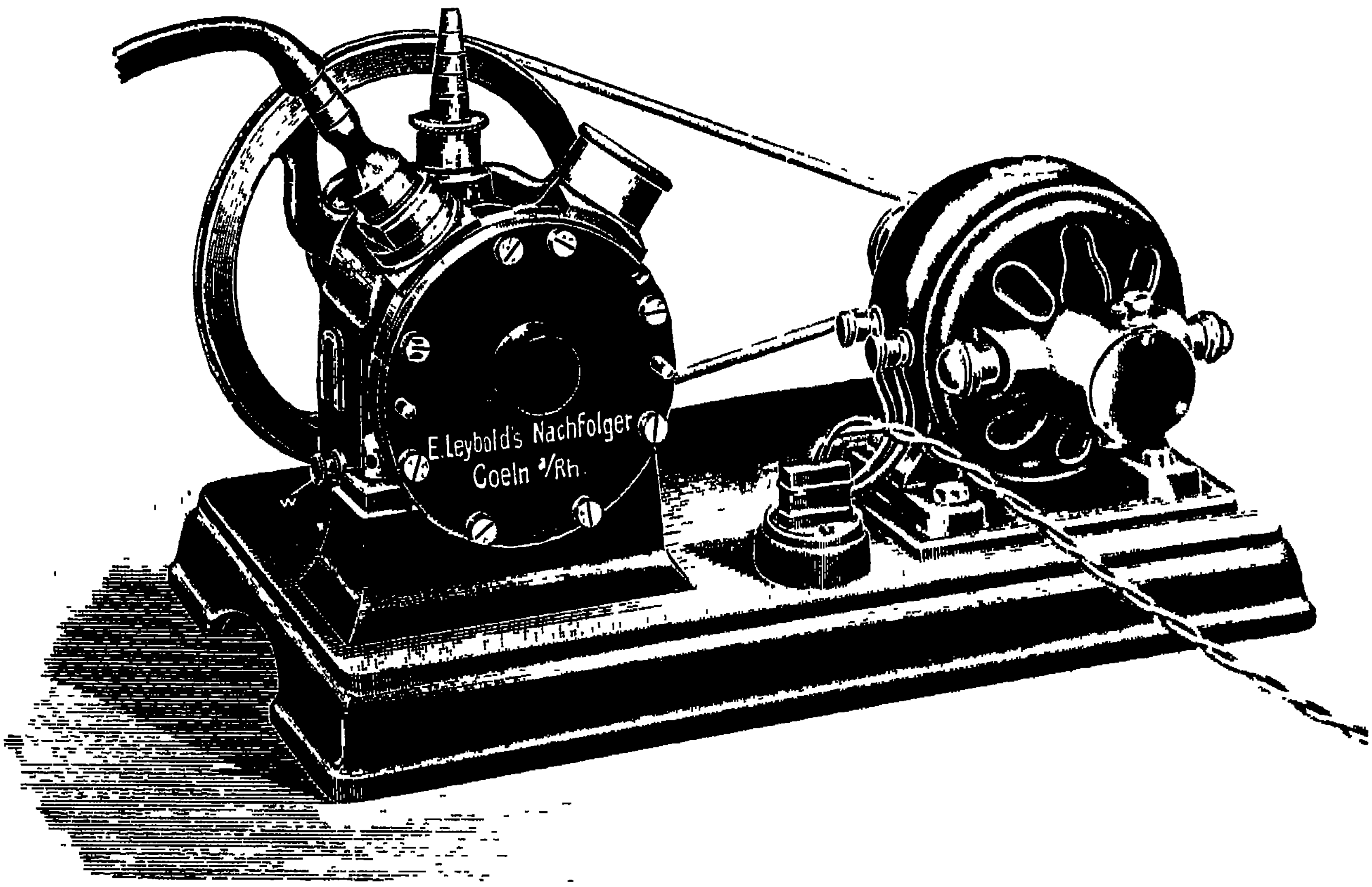



FIG. 6A.—Gaede Rotary Oil Pump.

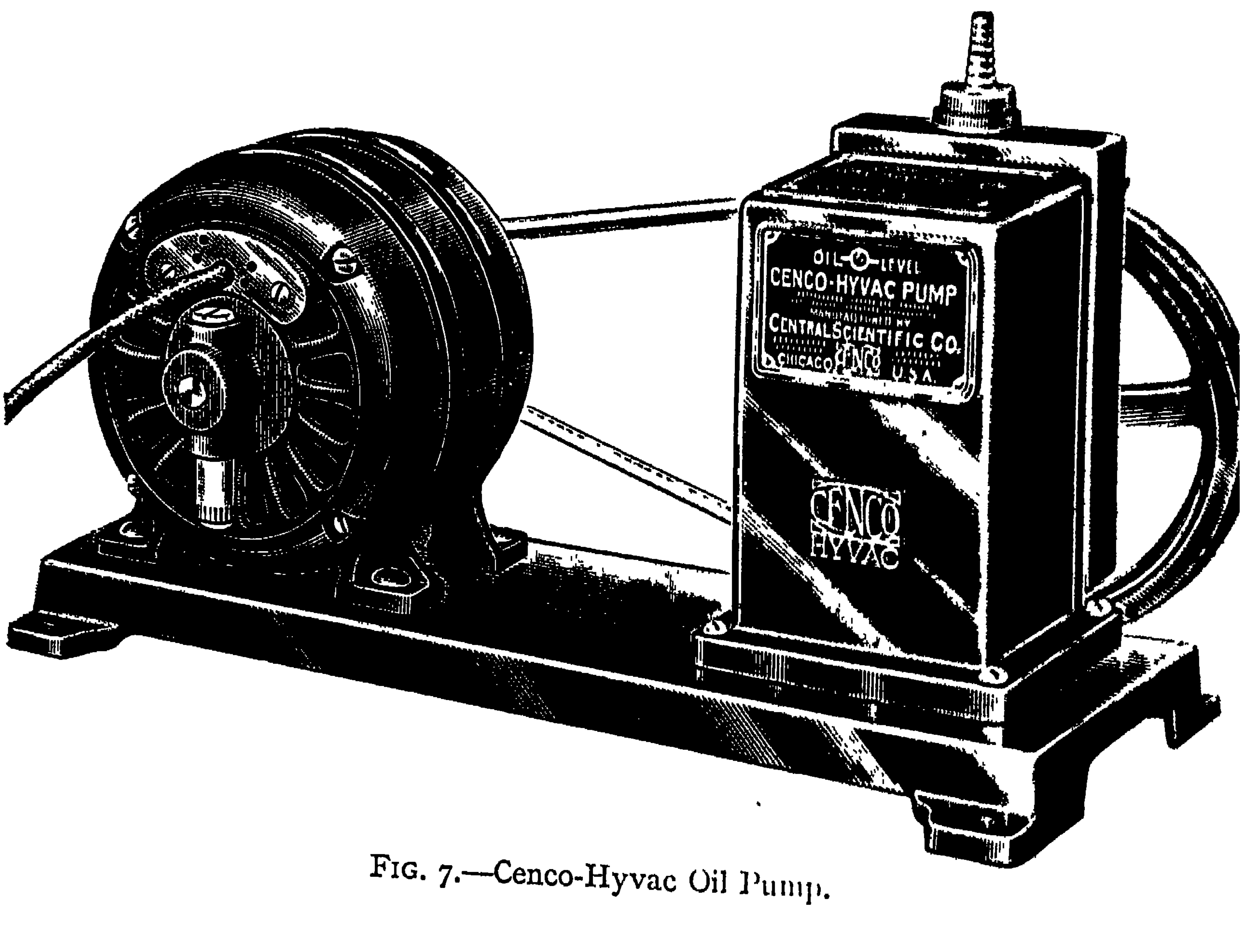



FIG. 7.—Cenco-Hyvac Oil Pump.

when the partition is not closed by mercury, the air is evacuated into the space *l*.

This pump has dimensions such that a pressure of more than 15 mm of mercury would be sufficient to cause the mercury to be forced up the tube R. It has therefore, in distinction to the pumps already described, to be used in combination with a fore pump of the type next described. The degree of final vacuum is dependent upon the value of this fore vacuum. This pump has been much used in electric lamp manufacture and for X-ray tube exhaustion. It allows a value of ·01 bar to be easily and rapidly reached. Its defect is that, after considerable use, rotation of the porcelain rotor is liable to cause cracks to develop in the porcelain, *viâ* which air leaks back.

*The Rotary Oil Pump.*—This type of pump is again originally due to

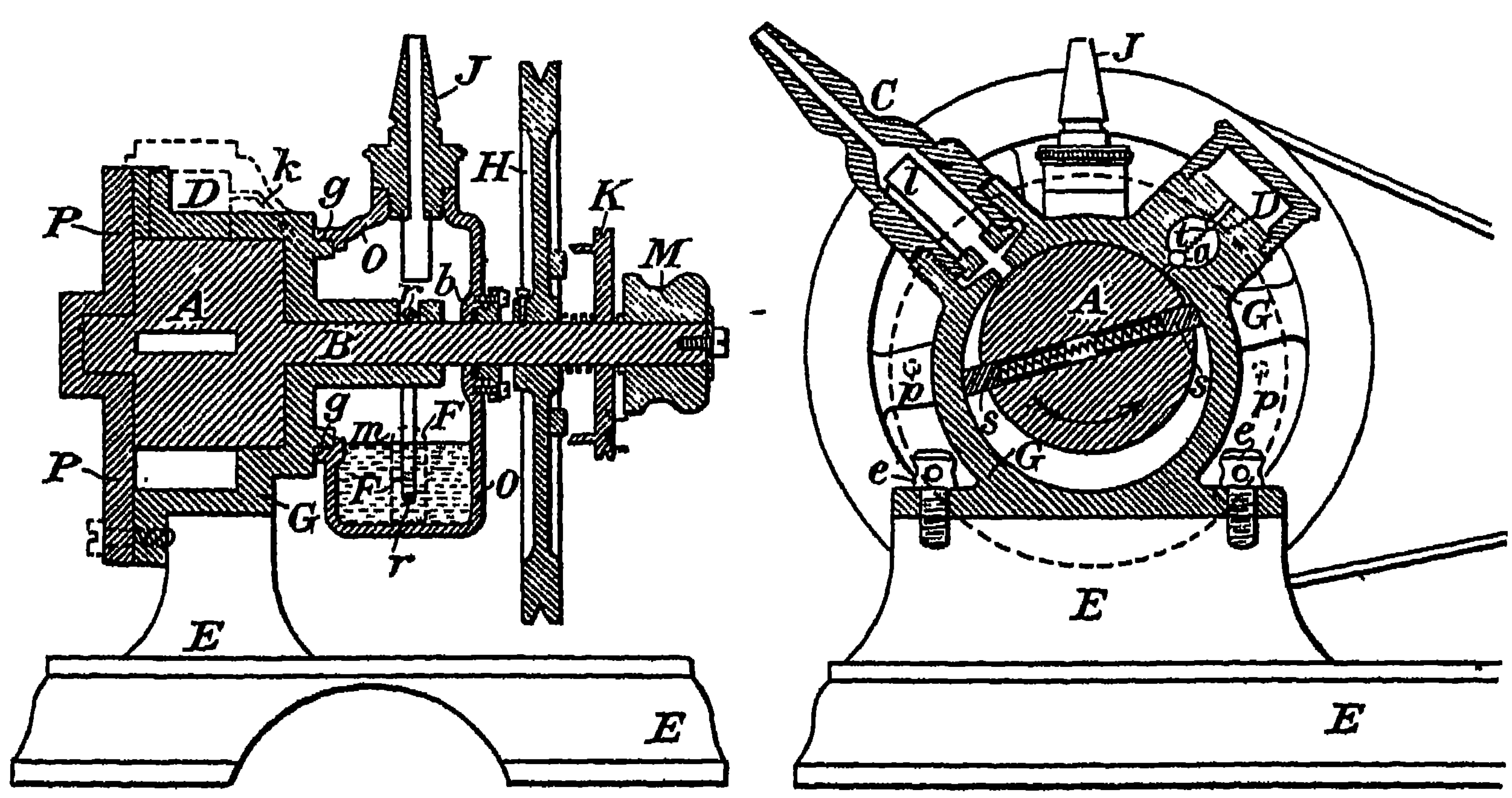



FIG. 6B.—Gaede Rotary Oil Pump.

Gaede, but many similar pumps have since been designed by other investigators based upon the same principle.

The Gaede pump (Figs. 6A and 6B) was intended to produce a fore vacuum for the rotary mercury and the mercury vapour pumps, and is essentially a hollow casting G within which is an eccentric steel rotor A. This rotor carries a pair of projections *s* of lengths practically equal to the diameter of the casting, a very tight fit of the projections being ensured by means of spring contacts, and the air between being closed by means of an oil lubricant. The effect of placing the rotor eccentrically is to cause the production of two unequal spaces to be made between the inner casting surfaces and the peripheral rotor surfaces.

In consequence, when the rotor is driven in an anti-clockwise direction the greater of these two spaces is put into communication with the space to be exhausted by means of the connection C. As a result part of the

gas in this vessel enters the large air space. Rotation of the roto separates this space from the connection C and further rotation d the gas to the exhaust valve D and exhaust J. Such pumps w 200 to 400 r.p.m. and allow a pressure of ·06 mm. of mercury obtained. If a fore vacuum is applied at J, by a similar pump acti fore pump, pressures as low as ·001 mm. of mercury can be obt Such pumps have been widely used in commercial lamp manufactu many forms are now existent. In a pump manufactured by the C Scientific Company of America the brush-like diametrical contact replaced by a brush which is fixed to the casing and presses upon carried by the rotor instead of *vice versâ* as in the original Gaede p

This pump is shown in Fig. 7 and in section in Fig. 8A. It diff design from the original Gaede pump as follows ;-

(1) The position of the movable vane C in the wall of the ou cylinder instead of in the rotor.

(2) The entire separation of the inlet (E) and outlet (F) ports times, by the sealing of the at two points (K and G), overcoming any possibility leakage.

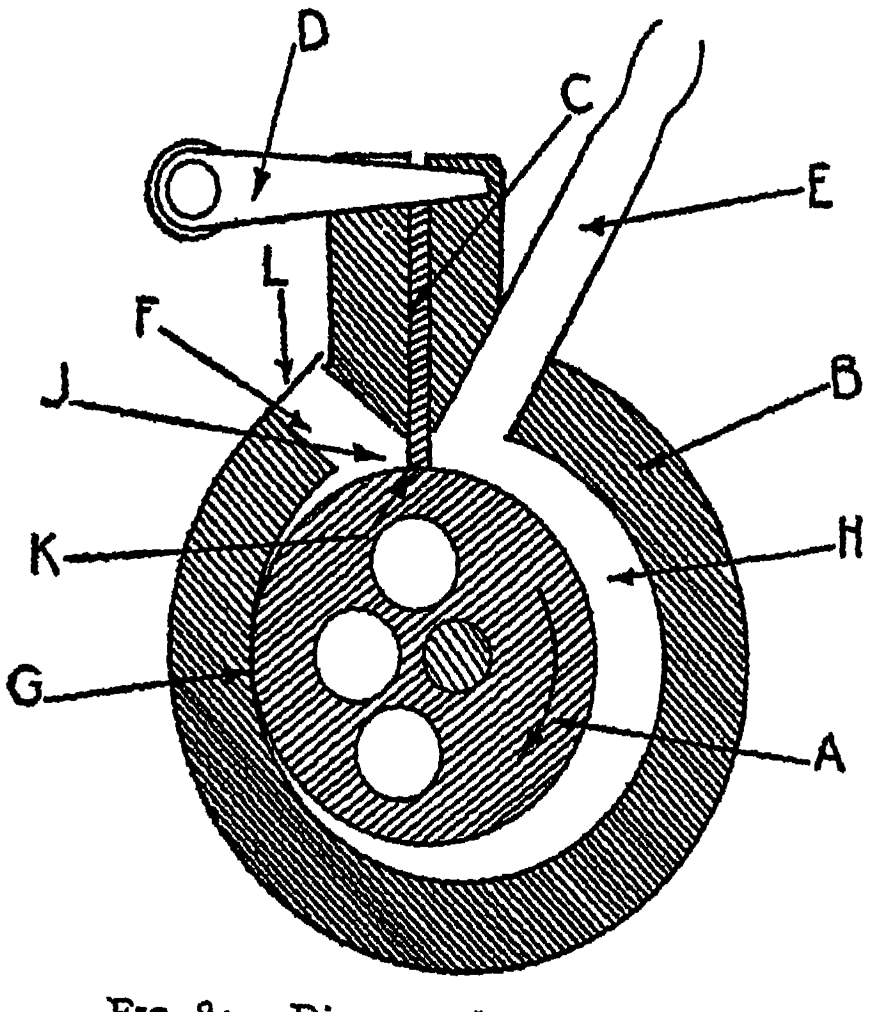



FIG. 8A.—Diagram showing essential features of Cenco-Hyvac pump.

(3) The location of the and outlet ports at the edges of the vane, which ins the removal of the air on outlet side before the inlet is uncovered and prevents diffusion of air back into vessel being exhausted.

(4) The use of two set parts, constituting a two-s pump, one of which acts backing or fore-pump, the o a finishing pump. This m the outfit entirely self - c tained.

(5) The entire immersion of the pump in carefully selected oil. effectually seals every surface and prevents any leakage from with It serves further to distribute any heat generated by the friction of rotor against the vane and thereby prevents displacement of the p through expansion.

(6) A low speed of rotation, made possible by the absence of leak which renders unnecessary any water jacket or cooling device, since temperature of the oil rarely rises above 40° C.

(7) The valve at the outlet (L), which cuts off the back pressure of

atmosphere against the rotor and thereby reduces to a minimum the power required to operate the pump.

(8) An internal steel trap at the inlet tube, which effectually prevents the " sucking back " of any oil into the exhausted vessel should the pump be stopped for any reason. The inlet tube ends in a corrugated hose connection with annular cup for oil or mercury seal.

(9) All working parts of the pump are of iron or steel, so that the pump cannot be injured by having mercury drawn into it from gauges or manometers. This feature is a great improvement over older types of pumps,

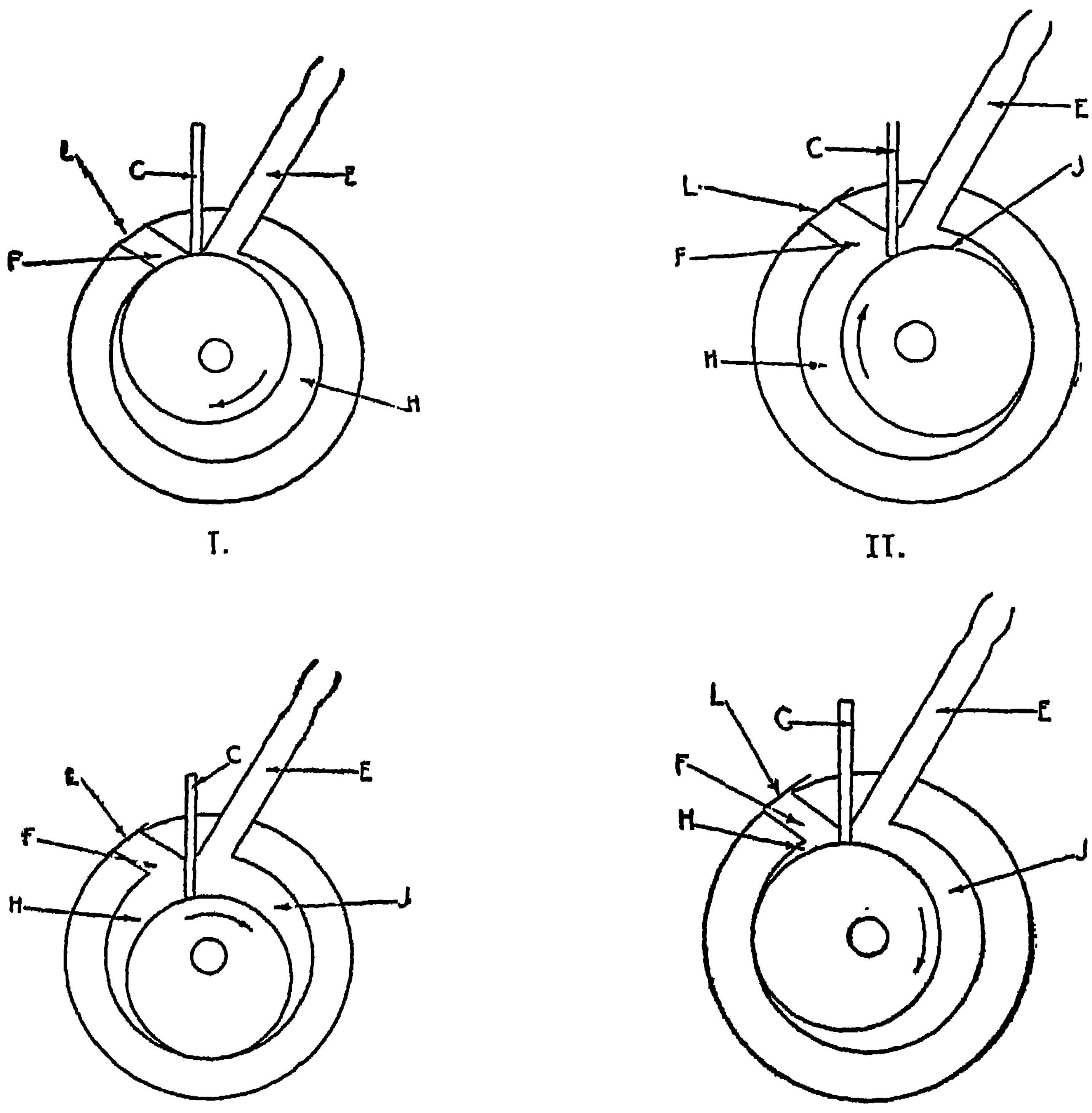



FIG. 8B.

which are frequently injured beyond repair by amalgamation of the brass parts.

The operation of the pump is easily understood from an examination of the four sectional diagrams (Fig. 8B), which represent one complete cycle. When the rotor is in position I. the vessel to be exhausted is connected through the open inlet tube E to the space H, which becomes filled by the expansion of the air in the vessel. When position II. is reached, the space H has begun to diminish in volume since the vane C which is held tightly against the rotor by spring pressure on the arm D, prevents the

air from following the rotor around. Additional air from the exhausted vessel expands to fill the empty space J left between the vane and the rotor, which increases in volume as the rotor continues toward position III. In position III., space H has become contracted about one half, so that if the air were unable to escape, it would be in a state of compression as compared with the air in the vessel, which would increase as the rotor moves toward position IV. Actually the air in space H cannot escape until it reaches a pressure equivalent to the sum of the pressure of the atmosphere and that of the oil above the valve L, since it must lift this valve against the combined pressure. When space H is entirely closed, the air has all been pushed into the outlet tube and the cycle is complete.

As shown in the phantom diagram (FIG. 8C), the Hyvac pump consists of two stages as described above, mounted vertically at a slight angle to each other, with the rotors mounted on a common shaft. The stages are securely attached to one vertical side of a square cast iron case, with removable lid. The horizontal shaft passes through a stuffing box, which can be tightened up as necessary to prevent leakage.

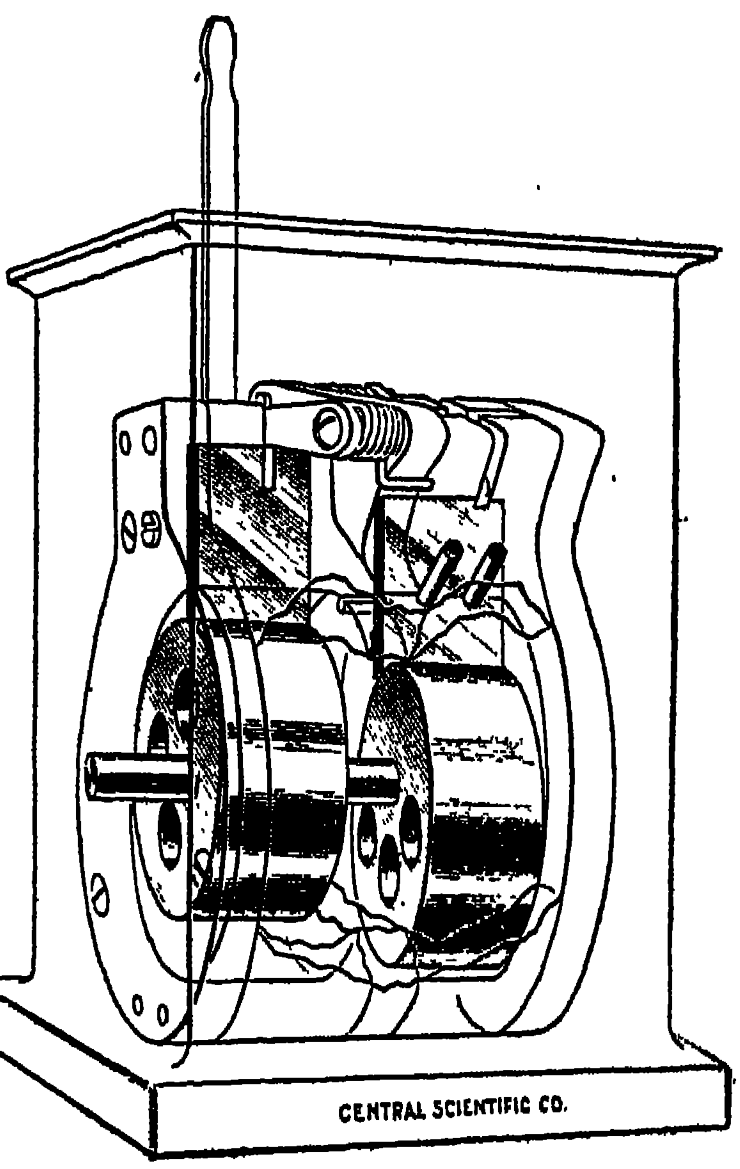



FIG. 8C.—Phantom view, showing arrangement of pump.

The shaft carries a 7 in. pulley, grooved for [illegible] in. round belt, which provides the proper speed of operation when connected to the usual fractional horse power, constant speed, motor.

The mechanical arrangement of the pump is such as to prevent the foaming or spattering of oil common to many oil-sealed pumps.

A further source of great annoyance to users of vacuum pumps is the "sucking back" of oil into the exhausted vessel if the pump is stopped without disconnecting the vessel. To prevent such a possibility there is an inlet trap, which effectually prevents the "sucking back" of any oil into the exhausted vessel, should the pump be stopped for any reason. The trap is contained within the pump, and, since it is valveless, it will always function. The inlet tube at the top of the pump is corrugated to take rubber vacuum tubing. An annular seal surrounds the inlet tube at the top of the trap, permitting the joint to be sealed with oil, mercury or with Wood's metal.

A two-stage pump more closely following the Gaede pump is shown in Figs. 9A and 9B. The outer cylinder A is a thick rigid casting which is

atmosphere against the rotor and thereby reduces to a minimum the power required to operate the pump.

(8) An internal steel trap at the inlet tube, which effectually prevents the " sucking back " of any oil into the exhausted vessel should the pump be stopped for any reason. The inlet tube ends in a corrugated hose connection with annular cup for oil or mercury seal.

(9) All working parts of the pump are of iron or steel, so that the pump cannot be injured by having mercury drawn into it from gauges or manometers. This feature is a great improvement over older types of pumps,

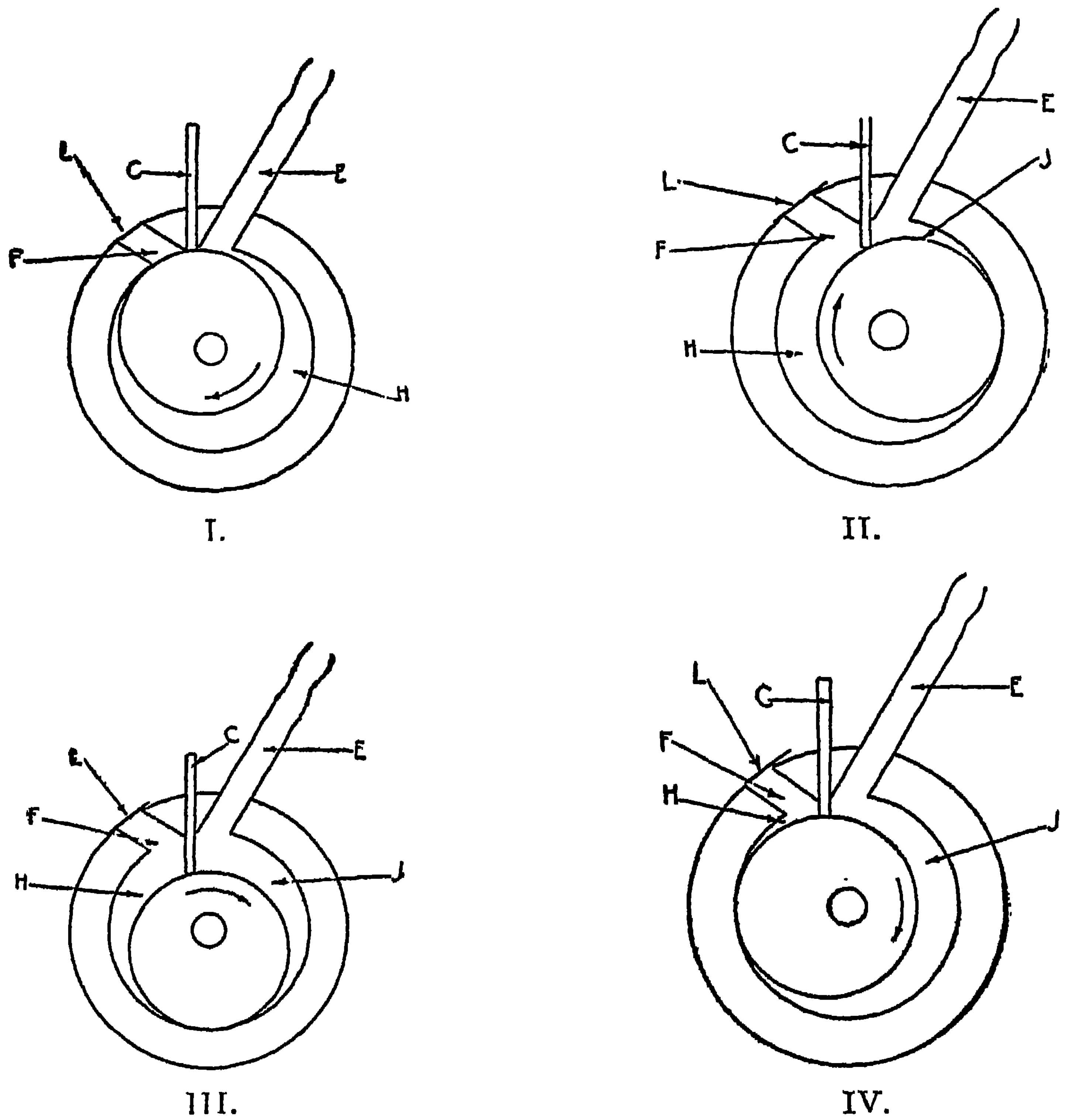
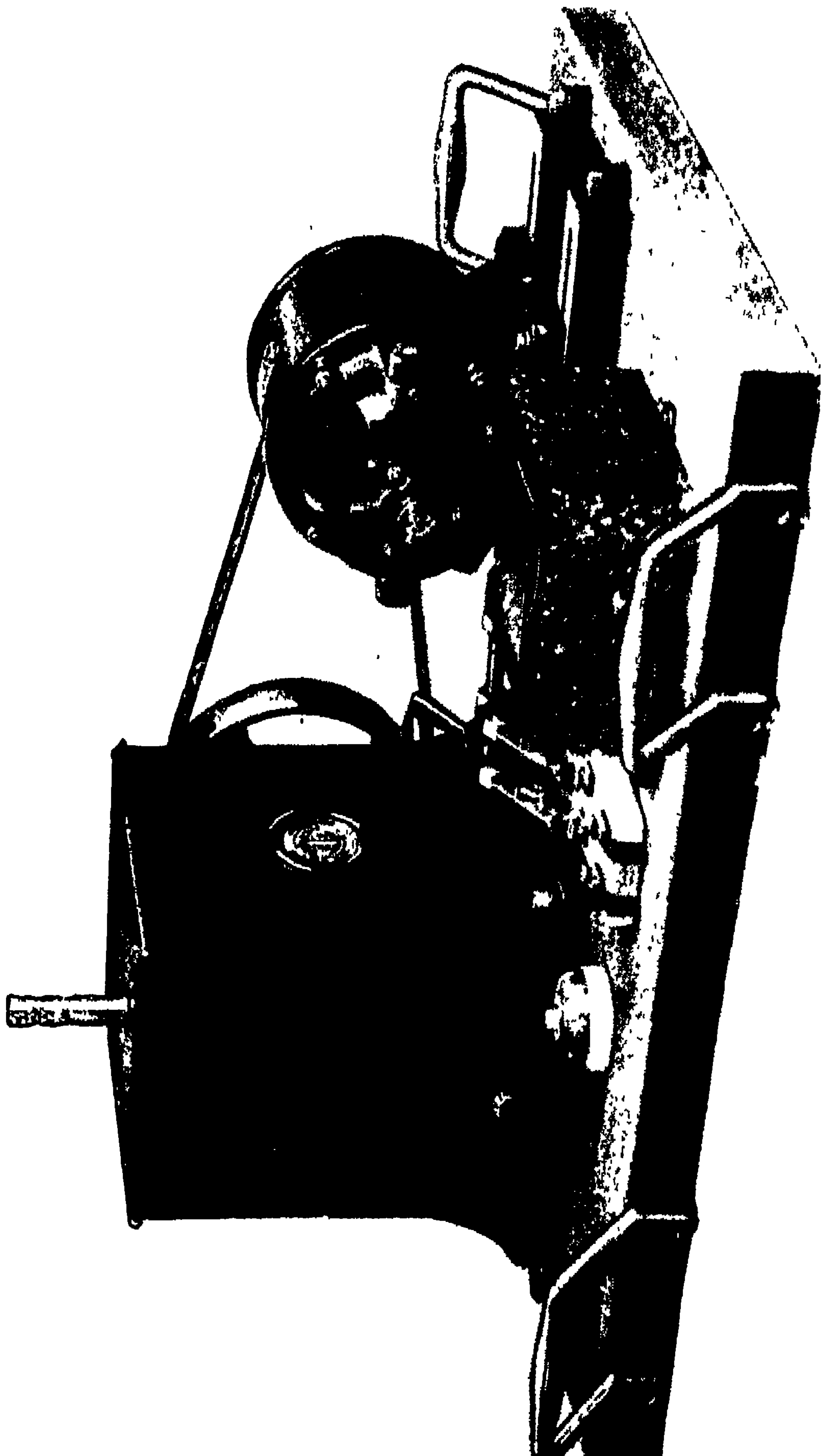



Fig. 8b.

which are frequently injured beyond repair by amalgamation of the brass parts.

The operation of the pump is easily understood from an examination of the four sectional diagrams (Fig. 8b), which represent one complete cycle. When the rotor is in position I. the vessel to be exhausted is connected through the open inlet tube E to the space H, which becomes filled by the expansion of the air in the vessel. When position II. is reached, the space H has begun to diminish in volume since the vane C which is held tightly against the rotor by spring pressure on the arm D, prevents the



bored and ground with great accuracy. The cylinder B rotates against A at the point marked D. Two plates, E and F, slide in a slot C and are pressed in contact with the inner walls of A by springs G. On rotating the inner cylinder in the direction of the arrow the air in the space I is compressed and escapes through the valve K. At the same time the volume of the space H is increased until the plate F passes the inlet tube. The air so trapped is carried round the cylinder and expelled at the valve K. The whole of the working parts are placed in an outer rectangular case filled with air-free lubricating oil, which ensures perfect lubrication, prevents leakage of air into the high vacuum and assists in efficient cooling of the

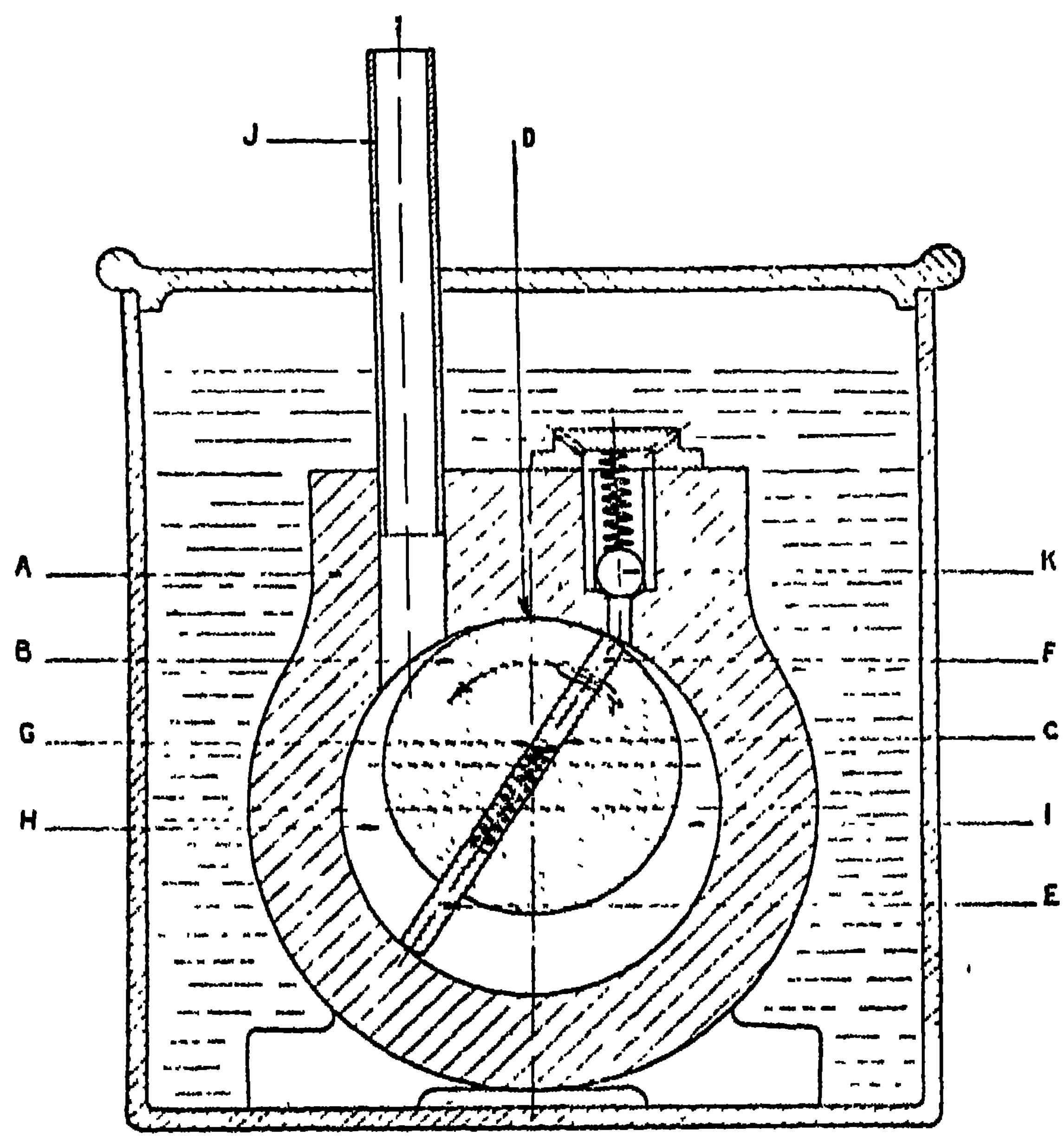



FIG. 9B.—Schematic Arrangement of Gaiffe Oil Pump.

pump. A sieve is placed in the tube J to prevent dirt and grit entering the pump. Both single-stage and two-stage pumps are made, and in the two-stage pump the connection between the two units is formed by the casing A and only one valve K is so needed. Pressures of 0·02 mm. with the single-stage and of 0·0001 mm. with the two-stage pump can be produced.

Trimont * in America has also produced a similar pump, in which the number of diametrical brushes are increased to eight, with the result that there is a far less risk of the revolving contact surfaces allowing communication between the space to be exhausted and the atmosphere, with consequent increase of pump efficiency.

* For further details see Dunoyer, "La Technique du Vide."

Other types of pump,* consist of two cog wheels, the interlinked cogs of which are arranged to entrap gas and to carry this to the exhaust. Prior to the production of molecular and mercury vapour pumps, these oil pumps had great application in the lamp industry. They are simple in manufacture, rapid and easily operated automatically. They all suffer to a more or less degree from the defect that whilst, when new, they are capable of giving a high degree of vacua, with constant use the close apposition of the moving surfaces causes wear in spite of the oil lubricant, and the larger clearances so formed allow gas to leak back into the evacuated space so that, with a worn pump, a pressure of not less than a few millimetres of mercury is only obtainable.

*Gaede's Non-Return Oil Pump.*—The immersion of the rotating case

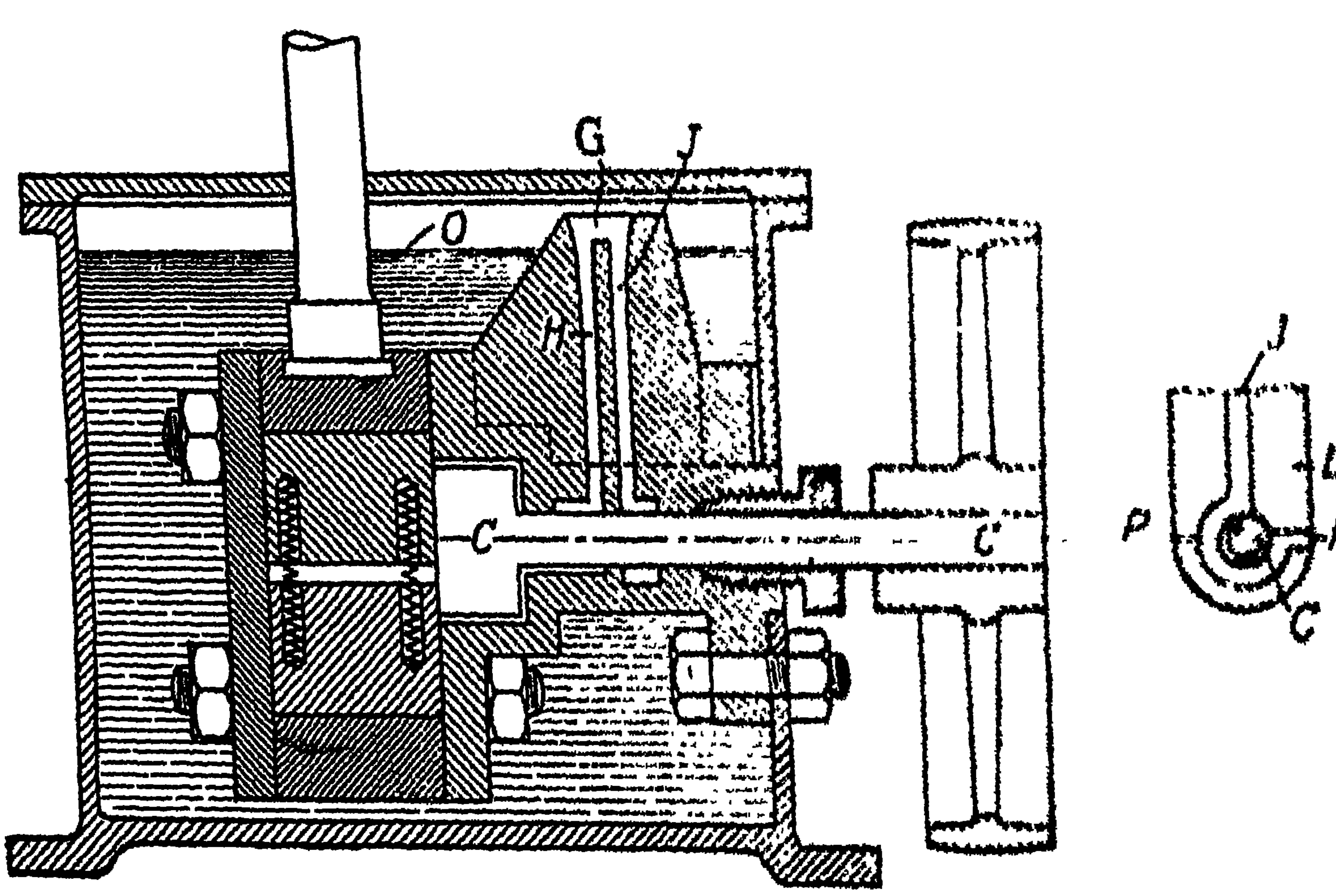



FIG. 10.—Improved Gaede Oil Pump.

of a pump in an oil-bath has the advantage of absolutely and reliably sealing off the pump. In such pumps the usual disadvantage is that on stopping the pump, oil passes back to the evacuated space. If it is forgotten to shut off the vacuum from the apparatus before stopping the pump, the whole apparatus is flooded with oil. In the latest Gaede oil pumps of iron this disadvantage is overcome. The improvement as shown in Fig. 10 consists in that the groove P which surrounds three-quarters of the circumference of the axle C is cut off in the bed L and sealed by N in the oil bath and by J in the bowl G, which must be above the oil level O. If the axle C rotates then the oil from N, passes by the groove P and the

* For further details see Dunoyer, "La Technique du Vide."

boring J. The greater part of the oil so flows back to the bath. The smaller part of the oil flows *viâ* the boring H to C and into the casing. If the pump ceases to rotate then no more oil rises to G and air is so pressed out of G to C and into the casing. On stopping the pump no more oil rises in the apparatus but air is slowly forced in, a circumstance which is clearly shown by experiments with the pump.

## THE MOLECULAR PUMP

This pump, again due to Gaede, marked a great advance over all previous types of pump. Vacuum pumps, prior to 1912, were either directly or indirectly of the von Guericke type, in which a certain volume of gas is separated from the vessel to be exhausted and then this separated gas is shut off by some form of piston or valve or, as in the mercury and oil rotary pumps, separated by the fluid level, the separated gas being finally exhausted into the atmosphere or fore vacuum.

In the molecular pump there is no such separation, but the gas is dragged towards the exhaust without the intervention of any valve.

Gases, like liquids, exhibit the phenomenon of viscosity, a property which prevents their rapid flow, a familiar example being tar, or a thick oil. When such a medium flows for example *viâ* a tube, the velocity of flow at the centre of the tube is greater than the velocity of flow of that portion of tar near the tube wall where the flow may be relatively small. Between these two extremes there is a continuous decrease of velocity of flow from maximal central to minimal peripheral velocity. This retardation is actually due to the occurrence of friction between the molecules of the liquid and the wall and is quite related to the friction between two solid surfaces.

A comparatively non-viscid liquid as water offers less internal friction, and for a given force (or hydraulic " head ") the velocity imparted to the fluid is greater than if the fluid is viscid and has a large internal friction, which must be overcome before movement can occur. The degree of viscosity is measured in terms of a *coefficient of viscosity*, usually denoted by $\eta$, for the exact definition and measurement of which text-books of physics should be consulted.

Instead of considering the flow of liquid relative to a fixed wall, we may consider the movement of a wall relative to a liquid assumed to be fixed in space. Were friction or resistance of viscosity entirely absent the wall would move and the fluid remain at rest at all points. As however friction is present, before independent movement of the wall can occur, work has to be done in order to overcome this friction. If the work expended is not very great, some of the friction is not overcome,

and fluid will tend to be dragged along by the moving wall, the amount and depth of which will be dependent upon the velocity of the wall.

As already mentioned (Vol. II.), gases exhibit internal friction, or viscosity effects, similarly to liquids. Gas molecules are however capable of a greater degree of movement than liquid molecules. Upon the kinetic theory a gas has all its molecules moving it all directions. If any particular molecule collides with a moving wall, the molecule tends to lose its kinetic energy and direction of motion, by having its direction of movement changed to the direction in which the wall is moving. Since the movements of gas molecules and their free mean paths are not so limited as in the case of more closely packed liquid molecules, not only those gas molecules in the region of the wall, but those more distant from the wall, will tend, after impact, to move in the same direction as the wall, since molecules which actually impact with the wall and receive its direction of motion will, by subsequent collisions with other gas molecules, tend to set these into motion in the same direction. As however at normal gas pressures the number of molecules per unit volume is great, any molecules, after impact with the wall, are unlikely to travel very far in the imposed direction of motion as this motion is rapidly destroyed by encounters with molecules which have not encountered the wall and are moving in other directions. In consequence this viscosity effect or movement of the gas in the direction of motion of the wall is not pronounced at normal pressures.

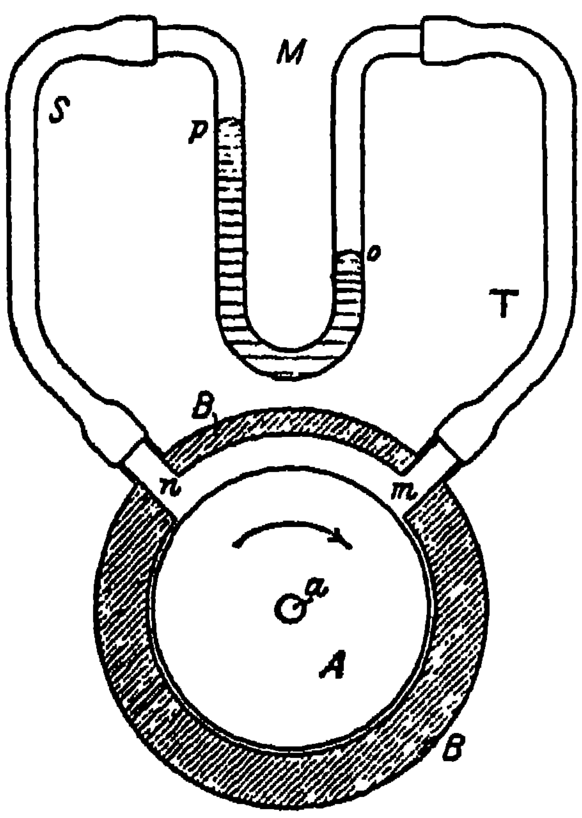



FIG. 11.—Action of Molecular Pump.

If however the pressure of the gas is reduced those gas molecules which, after impact, have obtained the same direction of motion as the wall, are not so liable to impact with other molecules and will tend to retain this direction of motion. Given a certain velocity of the wall and a suitable gas pressure the motion imparted to the gas may be considerable. The gas will therefore tend to be dragged along by the wall if this is given a sufficiently great velocity, and it is upon this viscosity dragging effect that molecular pumps depend for their evacuating action.

If in a cylinder (Fig. 11) with a rapidly rotating spindle we consider a molecule of gas at *n*, this will tend to take the direction of motion of the spindle and to be drawn in the direction *m*. If S is connected to a vessel to be exhausted, to maintain the pressure at *n*, further molecules will be drawn to the region *n* from S, and, if we have some form of fore pump drawing off the molecules at T which would otherwise accumulate at *m* and exert a back pressure, the net result will be that gas is continually

drawn off at S and exhausted at T, any vessel connected to S being so exhausted. In the diagram the difference of pressure at *n* and *m* is indicated by the levels *p* and *o* of the manometer M.

The actual form given to the molecular pump by Gaede is shown in Figs. 12A and 12B. To increase the viscosity effect of the rapidly moving walls, the surface area is increased by cutting into the rotor a number of deep slots D, which engage with a number of projections C and B on the stator, the distance of separation being in the region of ·1 mm. (Fig. 12A).

The vessel to be exhausted is suitably connected to the deeper central slots *viâ* T and the fore pumps to the outer slots *viâ* S, the pressure so

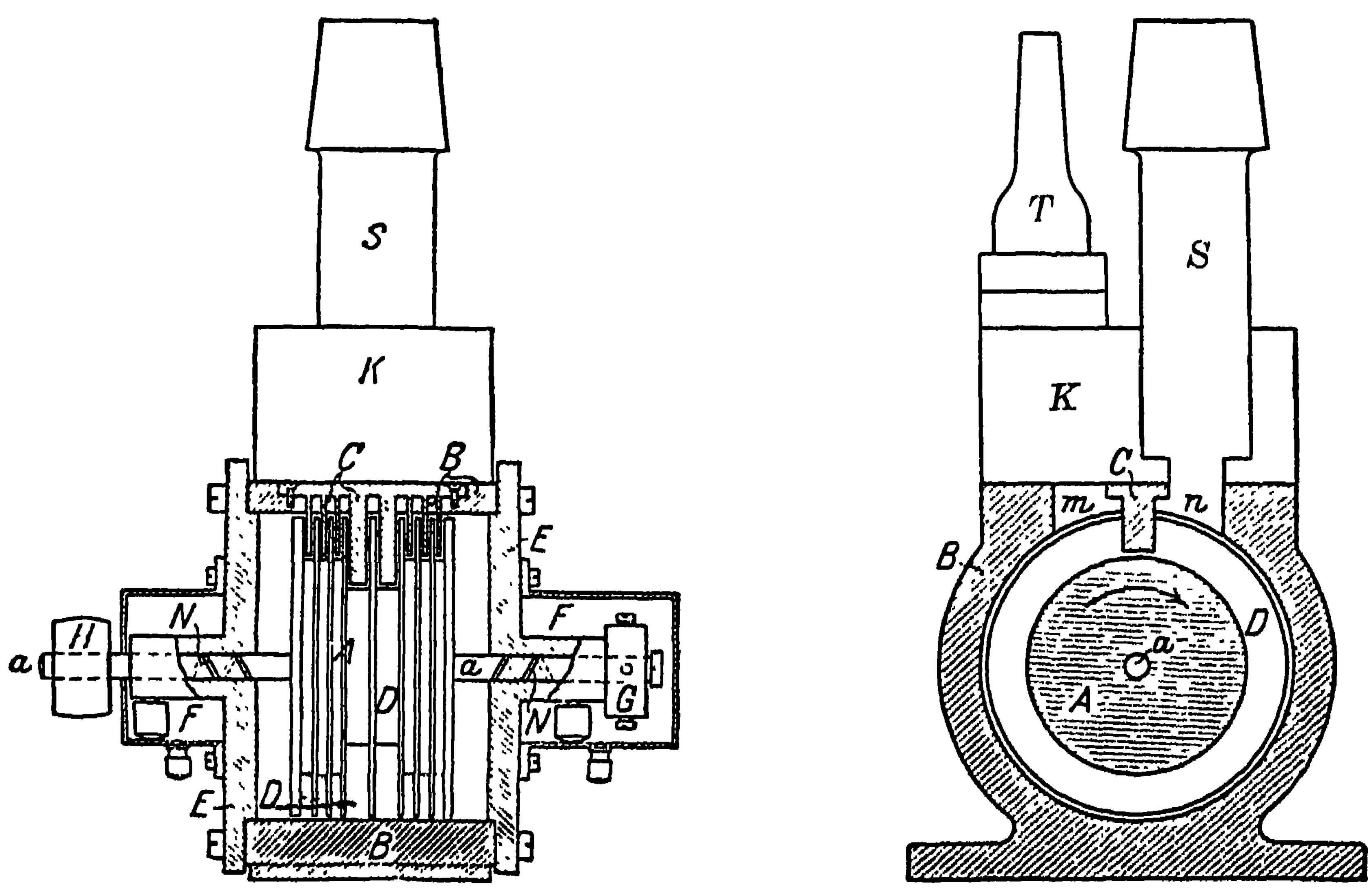



FIG. 12A.—Cross-sectional View. FIG. 12B.—Longitudinal View.
Sections of Gaede Molecular Pump (Messrs. Leybold, Cologne).

gradually increasing from within the pump outwards. The rotor is driven at a speed of 8,000 r.p.m. by means of a suitable electric motor, and oil cups are present upon the bearings at N.

These bearings are spiralar, so that the oil is continually forced out of the bearings to the interior and so prevents any entry of air *viâ* the bearings. For this reason the molecular pump has always to be started before the fore pump, as otherwise a continual air entry would result, and means to ensure automatically such prior starting of the fore pump are usually provided.

With a rough fore-pump pressure of 20 mm. of mercury it is possible to obtain a fine pump pressure of ·0004 mm. of mercury with this pump or even of $10^{-6}$ mm. of mercury.

Since its introduction this type of pump, in consequence of its robustness and convenience of operation, has been greatly used in the high-vacuum operations of industry, as lamp, valve and X-ray tube manufacture.

Whilst in turn these pumps tend to be replaced by the still later mercury vapour pumps, they have the advantage of not requiring frequent cleaning and renewal of mercury and are, in commercial use, free from

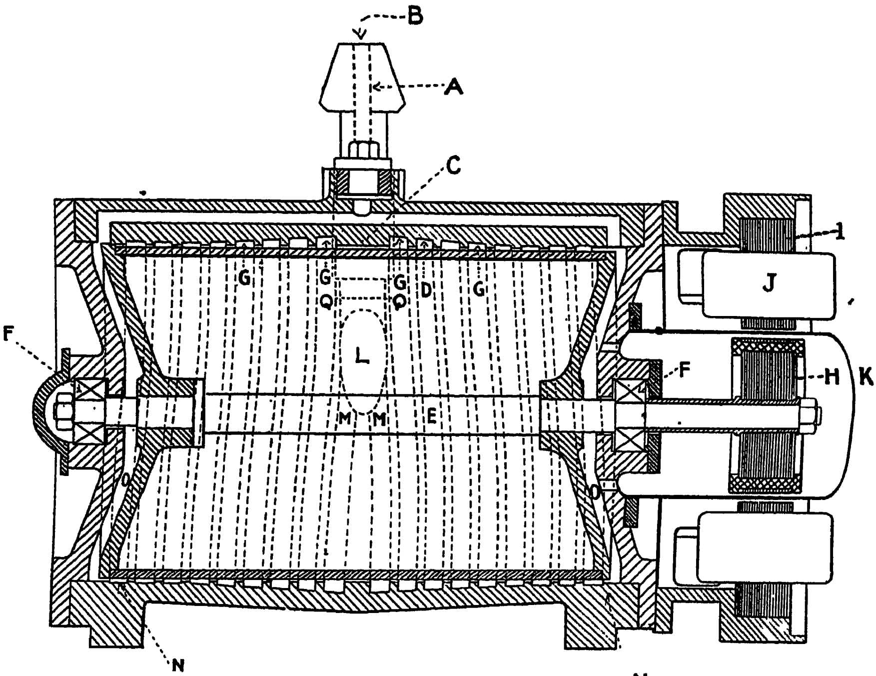



FIG. 13.—Holweck's Molecular Pump.

the danger of causing mercurial poisoning during such maintenance attendance.

Holweck * has improved upon this early pump by a type which has the following further advantages (Fig. 13) ;

(1) The rotor is totally within the low vacuum, so that the difficulty of leakage at bearings does not arise.

(2) The pump is mechanically more simple and in consequence the clearance distances are reduced from ·1 mm. of the Gaede pump to ·03 mm., with consequent improved exhaustion, as there is less risk of molecules passing from groove to groove around the projections rather than along the grooves around the circumference.

* *Journal de Physique*, 3, p. 64, 1922 ; *Revue d'Optique*, 1, p. 274, 1922.

The rotor has no grooves upon it, whereas the stator has a series of grooves turned in it from the centre to the ends in descending order of depth. The rough vacuum exhaust is *viâ* B and the fine vacuum is at A in communication with the port L shown in section. The rotor is driven by an alternating-current synchronous motor having stator coils J and non-connected rotor H, completely enclosed by a constantin shield K, which serves to enclose completely the pump rotor and motor rotor in the low vacuum and so to obviate bearing difficulties at F.

The lubrication required is very small, it being stated that it is only necessary to supply a small drop of oil to ensure three months' commercial operation, and there is therefore no risk of oil entering the vacuum, as may occur with the Gaede pump.

The rotor speed is 4,000 r.p.m. With this speed a pump of 150 mm. diameter and 220 mm. length and $7 \times 2$ grooved helices will, with a fore vacuum of 1 mm. of mercury, reduce the pressure of a vessel of 5 litres capacity from ·1 to ·001 mm. of mercury in ten seconds. It is stated the speed of this pump is 2,300 c.c. per second as compared to 1,100 c.c. per second with the original Gaede molecular pump.

As with all pumps working in conjunction with mercury pumps, it is preferably constructed of steel only, to prevent trouble due to entry of mercury amalgamation with other metals.

## MERCURY VAPOUR PUMPS (DIFFUSION PUMPS)

Mercury vapour pumps represent the most modern type of pump for production of the highest vacua and date from 1914. They are again due to Gaede,* although subsequently modified by Langmuir and others.

Some confusion arises since, whilst Gaede termed his pump a "diffusion pump," Langmuir has given his pump the term "condensation pump." The Langmuir pump is equally a diffusion pump, whilst in the Gaede pumps forced condensation of the mercury vapour, originally employed by Gaede, is carried out as in the Langmuir type of pump.

These pumps depend upon gaseous diffusion. It is well known and capable of experimental proof that if two vessels containing gases of highly different atomic weight and density, for example hydrogen and oxygen, are put into communication, then in spite of the difference of density, the gases will be found to mix intimately. For example if the vessel with hydrogen is placed above that of the oxygen then, after a given time, the heavier oxygen will be found in the lighter hydrogen and hydrogen in the heavier oxygen.

The explanation is based upon the kinetic theory of gases. At any given pressure the molecules of gas have an average "free mean path," which is the average distance a molecule travels before it undergoes

* Brit. Patent 19,793/1914.

impact with another molecule and, as a result, has its direction of motion changed (see Vol. II.).

At the line of demarcation of two gases, in our example hydrogen and oxygen, in consequence of this molecular movement molecules of hydrogen will be projected into the oxygen zone and oxygen molecules into the hydrogen zone.

Some of these molecules will undergo repeated impacts with other molecules and their directions of motion be so changed that they will be unable to return to their original locations and subsequent impacts will tend to drive them deeper and deeper into the other gas. So their return is still more impossible, as in order to do so they would have to undergo many specific impacts, all favourable to motion in one direction.

It is well known that the rate of such diffusion is inversely proportional to the square root of the gas density (Graham's Law of Gaseous Diffusion). Upon the kinetic theory it can be shown that such a law must hold, in view of the different kinetic energies of the gases in terms of their masses.

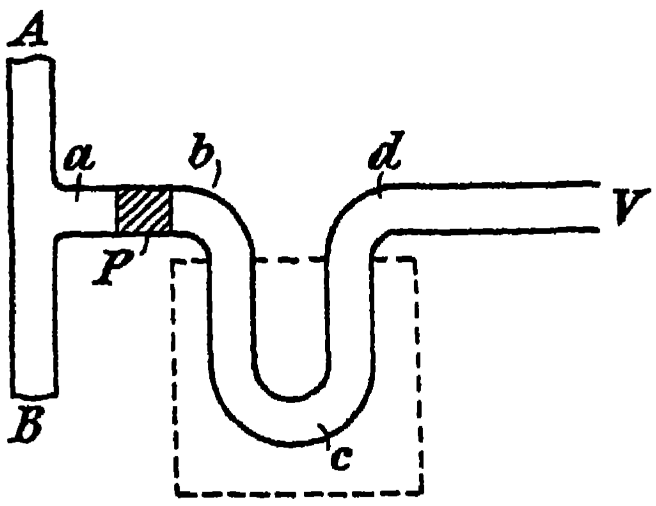



FIG. 14.

If we consider a vapour, such as mercury in a tube AB (Fig. 14) and a gas in a vessel at V, vapour will diffuse along the tube *abcd* from AB to V, and gas from V to AB.

If further, we cause a blast of mercury vapour to pass along AB, any gas which has diffused from V to AB will be removed from the system, as such gas molecules have less energy than the energy of the more swiftly moving and more heavy mercury molecules which, in consequence, give them a greater velocity in the direction of the mercury vapour motion, than the gas molecules can impress upon the mercury molecules.

In consequence of this the partial pressure of the air at *a* becomes progressively smaller and air diffuses *viâ a* and AB from the vessel V, until there is no longer air in the vessel V. Meanwhile the vessel V has been filled by vapour diffusing from *a* to V, so that the total pressure of air and vapour remains as before. If we entrap the vapour at *c* by immersing the tube in cold water, or better still, liquid air, then no vapour passes to V, but the air can then no longer diffuse from V, since the vapour current from *a* to the point of freezing is so powerful that it forces all the air back to V, just as steam emerging from a boiling kettle, forces back the air of the atmosphere.

In spite of this Gaede showed it was possible to cause a diffusion of air from V to AB, by inserting a porous body at P, which so greatly lowered the current velocity of the vapour passing from *a* to *c* that the velocity, with which the air diffuses through the vapour from *d* to *c*, is greater than

the velocity of the vapour from *a* to *c* Then, as in the first case, there results a movement of air from V to AB. A difference however arises since in the vessel V not only does the partial pressure of the air steadily diminish, but also the total pressure falls, since no vapour passes from AB to V. The total pressure in V is now equal to the partial pressure of the air in V, *i.e.*, the vessel connected to V is exhausted, and the device acts as a vacuum pump. Gaede termed this a *diffusion* pump.

A diffusion pump, in which the air must pass *viâ* a porous body P, has a very slow pumping velocity, and, in the practical pumps, Gaede has

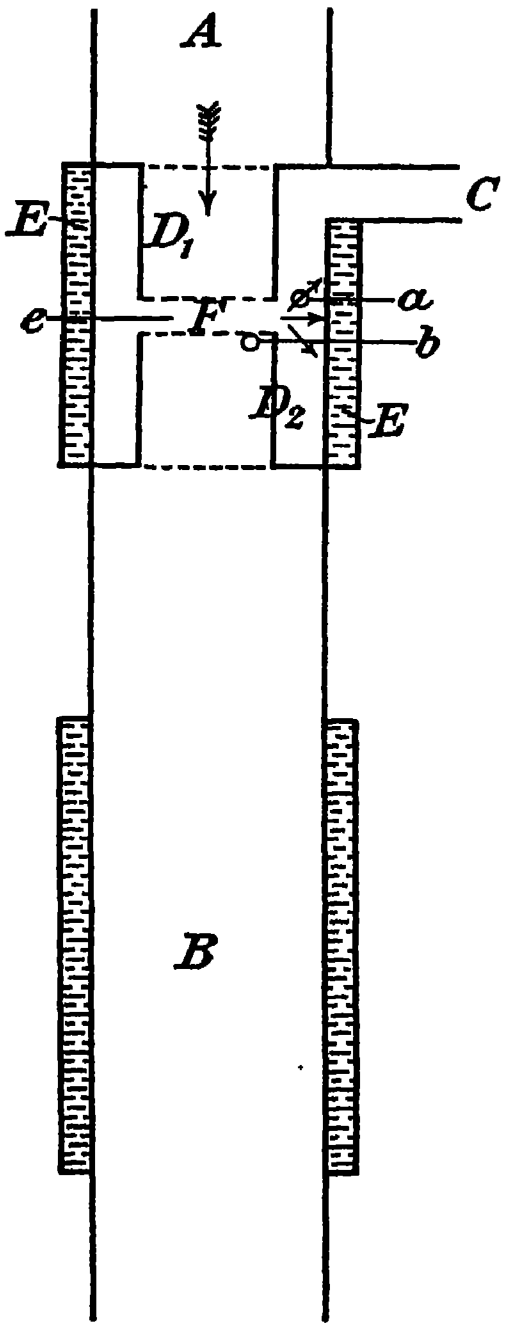



FIG. 15.—Schematic Gaede Diffusion Pump.

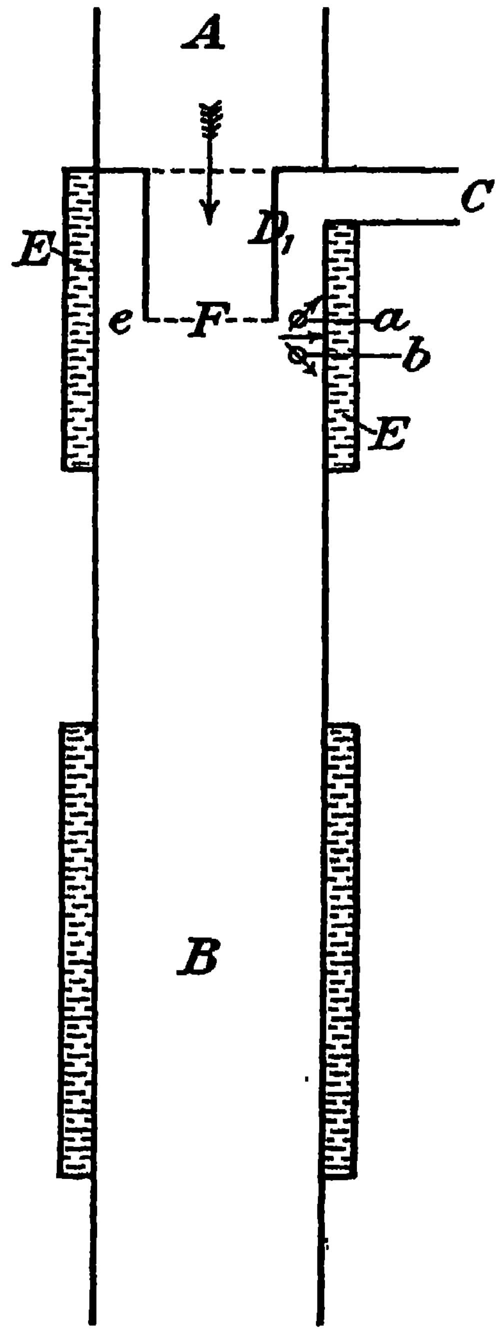



FIG. 16.—Schematic Langmuir Diffusion Pump.

obtained the same effect without a porous body in the following manner. By means of a fore pump the vapour pressure in the vessel AB is greatly lowered, and the diffusion velocity is thereby so much increased that the diffusion velocity of the air in the direction *c* to *a* is greater than the velocity of the vapour in the direction *a* to *c*.. This is the fundamental diffusion principle of all high-vacua vapour pumps independently of their manufacture, and whether they are known as injector or parallel stream pumps.*

The advantage of the Gaede diffusion principle for high-vacua pump construction is, firstly, owing to the high vacuum which may be obtained

* Gaede, *Zeits. f. tech. Phys.*, 4, p. 337, 1927.

and, secondly, to the high pumping velocity. The limit of vacuum obtainable is determined by the partial gas pressure in AB.

Since it is very easy, by boiling, to render liquids (*i.e.*, mercury) so air free that no trace of gases can be found in the vapour flowing *viâ* AB the vacuum in the vessel V can be immeasurably high.

Secondly, the pumping velocity of this type of pump is very great (the largest Gaede diffusion pumps have a velocity of more than 200 litres per second) since in rarefied mercury vapour the gas can obtain an extraordinarily high diffusion velocity.

The mode of action of the practical high-vacuum vapour pump (diffusion air pumps) can be seen from Fig. 15 and Fig. 17 shows the original Gaede arrangement. Fig. 16 shows the improved form of Gaede diffusion pump due to Langmuir. In Fig. 15 a boiler is connected at A in which air-free mercury vapour is produced. At B, by means of a fore-pump the gas which comes from the vessel to be pumped *viâ* C, is carried off. The vapour which passes from the boiler *viâ* A, in the direction of the arrow, largely flows into the fore vacuum space B and is then condensed upon the cooled walls. A smaller proportion of the mercury vapour flows *viâ* the slit *e* between the vapour tubes $D_1$ and $D_2$ in the direction of the smaller arrows, upon the cooled walls E, and is thereby liquefied. A suction action can arise when the air molecules, denoted by the small circles, come from the vacuous space *a* to the vacuous space *b*, *i.e.*, in other words, when the gas can diffuse from *a* to *b* against the vapour current denoted by small arrows. From *b* the gas molecules are then carried to B by the vapour stream. The diffusion from *a* to *b* can only occur when the free molecular path, on the high-vacuum side of the slit *e*, is so great that a considerable part of the molecules are in free flight, *i.e.*, not undergoing collision with, and being repelled by, vapour molecules moving in the opposite direction, in the path between the small circle *a* to the small circle *b*. If the free path is too small then the gas molecules going *viâ* *a* are repulsed by vapour passing out of *e* in the directions of the arrows and hence no vacuum can result.

Gaede has investigated this diffusion process mathematically and found it is determined by the quotient of the free mean path and the width of the slit. The condition to be fulfilled upon the high-vacuum side for evacuation to occur, is that the free mean path must not be less than the slit width.

Gaede carried out his original measurements with a pumping arrangement as in Fig. 17 and he showed that by using mercury vapour the highest degree of vacuum could be obtained.

The first model of a high-vacuum diffusion pump is shown in Fig. 17.* For the vaporising liquid mercury was chosen, since the free molecular path in saturated mercury vapour is sufficiently great (5 cm.) at the

* Gaede, *Ann. der Phys.*, 46, p. 357, 1915.

temperature used and mercury is therefore specially suitable for the diffusion principle. The mercury is heated by an external flame and the vapour in A flows *viâ* the steel cylinder *b* in the direction of the arrows through the tube to the condenser C in which the water for cooling enters at *m* and leaves at *n*. The drops of condensed mercury flow back to Q. The steel cylinder is set in a mercury-filled groove *d* and thereby the space

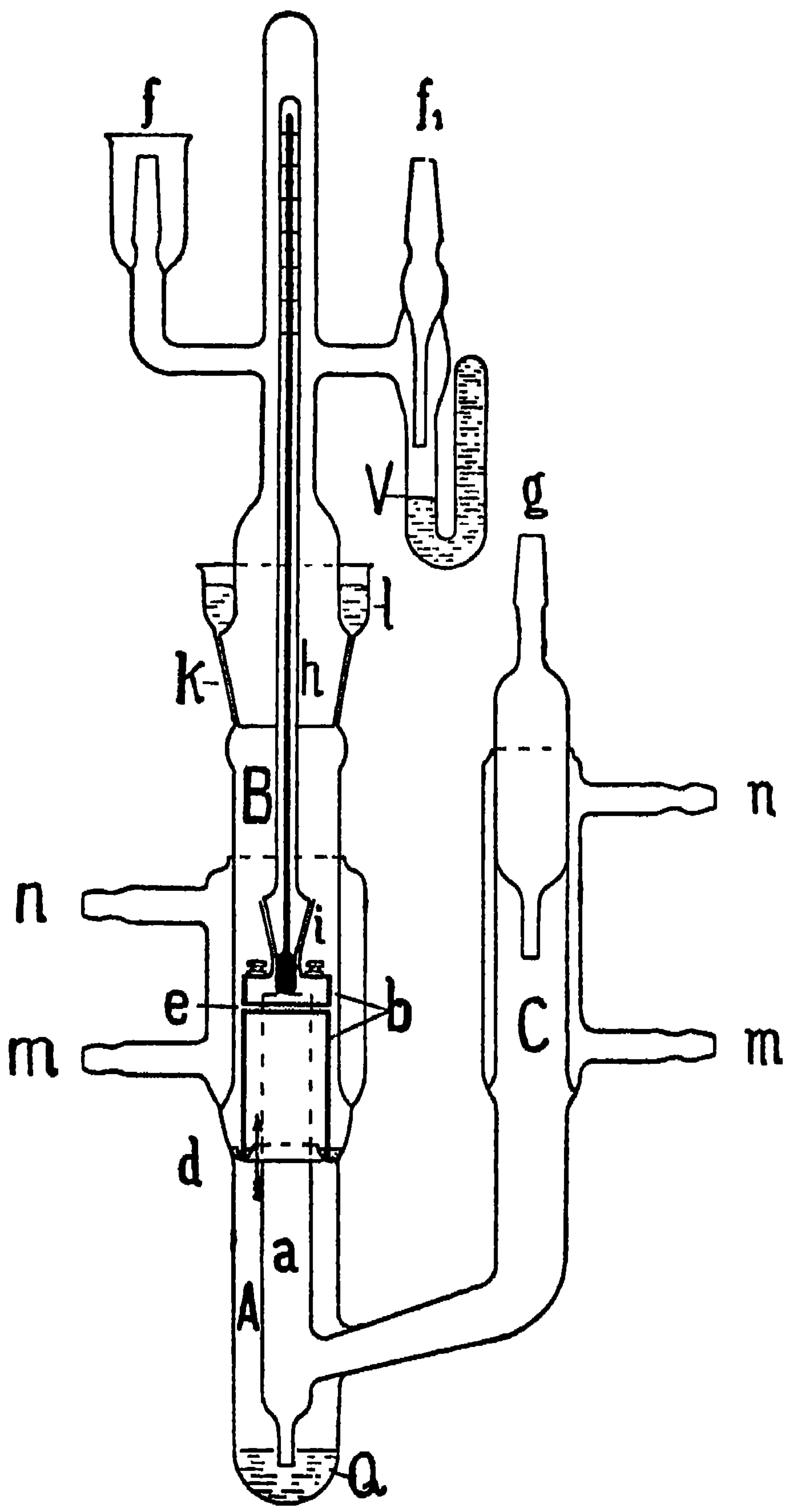



FIG. 17.—Gaede Diffusion Pump (Messrs. Leybold, Cologne).

A is shut off from the space B. The only communication between A and B is *viâ* the slit *e* in the steel cylinder. Part of the mercury vapour flows from the space A to the space B *viâ* the slit and is condensed on the cooled walls of B. The mercury so condensed flows to the channel *d* and so passes back to Q. The air which is present in the space B diffuses against the mercury vapour *viâ* the slit *e* and passes to the fore-pump connected at *g* by the tube *a* and the condenser C. In this way a vacuum arises in the space B and hence in the vessel connected to *f*. The thermometer *h* allows the measurement of the temperature of the vapour and from this,

in order to confirm theoretical calculations, the vapour pressure and the free mean path of the vapour molecules can be derived. By regulating the flame the temperature, and therefore the free mean path, which gives the best results, can be adjusted. With a slit width $e$ of 0·1 mm. the velocity of this pump is 80 cm. per second.

With this original Gaede diffusion pump and a fore vacuum of a few millimetres pressure, a fine vacuum pressure as low as ·00006 mm. of mercury could be produced.

The speed of exhaustion was however small and much inferior to Gaede's molecular pump, being of the order of 100 cm.$^3$/sec. (varying with the slit width), as compared to the molecular pump giving speeds of 1,100 cm.$^3$/sec. and the later Langmuir pump, where speeds of 4,000 cm.$^3$/sec. can be obtained.

In improved Gaede pumps with a slit width of 1 to 3 mm. this type of pump (Fig. 25) can pump up to 5,000 cm. a second.

Williams,* after proposing to vary the slit width, described a diffusion pump without such a slit. Langmuir adopted the arrangement shown in Figs. 16 and 20, where the slit is entirely absent and, in consequence, the effect of mercury vapour temperature is of comparatively negligible importance.

If in Fig. 15 we omit the tube $D_2$ we then obtain the arrangement of Fig. 16. This change in the Gaede pump is much used in practice. The mercury vapour strikes the lower edge of $D_1$ and indirectly, the cooling surface E, and then disperses in all directions as shown by the small arrows of Fig. 16. The pumping action occurs in the same way as in Fig. 15, and thence a high vacuum arises. A large part of the gas molecules in free flight are repulsed from the small circle $a$ to the small circle $b$ and *viâ* $b$ against the cooled wall E in the direction of the arrow and are then sent downwards to the fore vacuum. When the path of free flight $ab$ (that is the free mean path of the gas molecule) is smaller than the width of the diffusion slit which is bounded by the lower edge of $D_1$ and the wall E, then all the gas molecules in the path $a$ to $b$ are driven upwards in the direction of the upper arrows by the vapour and the pump gives rise to no high vacuum.

As is apparent from the previous discussion, a very wide variation of the external form of the pump is possible. If the diffusion principle is correctly chosen all pumps are characterised by the high vacuum obtainable and the high pumping speed. As soon as the surprising action was made known and the new theory of the pump detailed by various publications, modifications were introduced known as condensation pumps, parallel stream pumps, high-vacuum vapour-jet pumps, high-vacuum vapour-injectors, etc. All these pumps have the same characteristics detailed by Gaede in his first publication, namely, the free mean path of the

* *Phys. Rev.*, 7, p. 583, 1916; *Amer. Phys. Soc.*, 1916.

gas molecule in the vapour stream, must not exceed the width of the slit opening. The various groups of names only arise since the distinction between injector or vapour-jet pumps and diffusion air pumps was not clearly recognised.

The figures showing the stream lines (Figs. 18 and 19) make this distinction clear.* In the vapour jet pump (Fig. 18) the vapour flows *viâ* F from the jet and is held together as a vapour jet by the pressure of the surrounding air. At the boundaries of the moving vapour and the non-moving air, eddies are formed, which mixes the air with the vapour and takes it below. The continuous stream lines represent the vapour and the broken stream lines the sucked-in air The diffusion pump (Fig. 19)

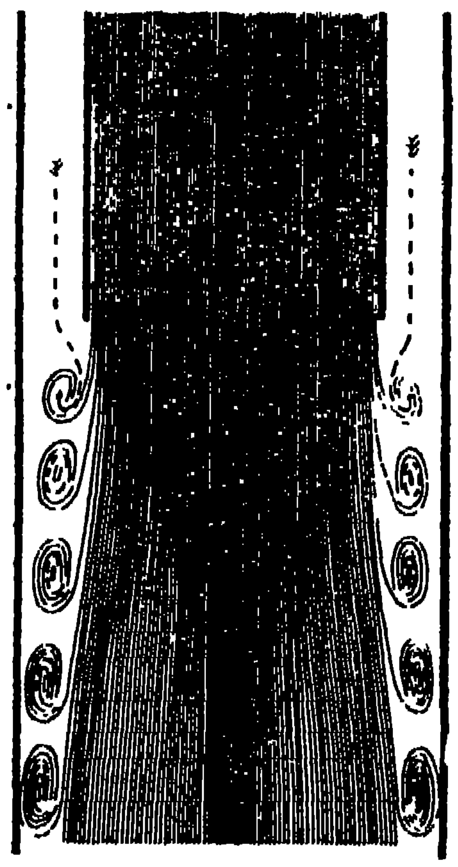


FIG. 18.—Vapour Jet Pump.

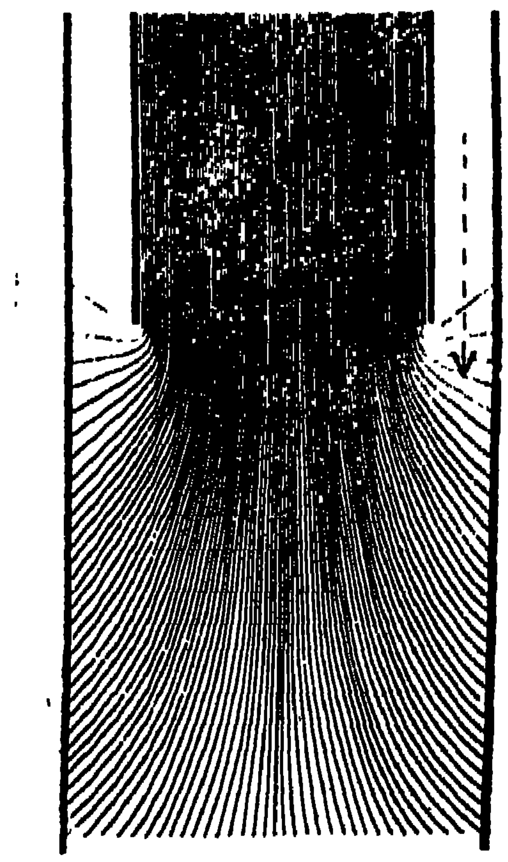


FIG. 19.—Vapour Diffusion Pump.

has a form which is not different from the vapour jet pump and the difference is in the physical action. As soon as, with lowering of pressure, the dimensions of the width of slit and the free mean paths of the molecules become the same, the characters of the stream lines completely alter. The vapour then enters *viâ* F in the form of vapour spray shown in Fig. 19, and the stream lines lie together more closely the greater the density of the gas. The distance between two stream lines is a measure of the size of the free mean path at any place. As the punctuated arrows denote, the air molecules pass *viâ* the upper less dense part of the vapour spray into the lateral directioned stream lines, and are here carried by the vapour to the walls and then downwards.

We know that the part of the vapour spray which passes backward is very dilute in comparison to the vapour near and below F. The unequal distribution of density is caused by the alteration of the Maxwell law of partition of velocity of any molecule passing out in a sideward direction

* Molthan, *Zeits. f. Phys.*, 7, p. 377, p. 452, 1926.

from the central vapour stream. The vapour molecules repulsed upwards move with a velocity which equals that of the non-altered thermal molecular velocity less the emerging velocity of the vapour stream. Only those vapour molecules can pass upwards having a thermal molecular velocity greater in the upward direction than that of the emerging velocity in a downward direction. We have then quite a similar relation to that we have learnt to be the case in the molecular air pump. Here only those molecules, which have a velocity in a direction contrary to the direction of rotation of the rapidly revolving cylinder, pass to the high-vacuum space and whose thermic molecular velocities are greater than the rotational velocity of the cylinder. If the emerging velocity of the vapour equals the velocity of sound then the number of upwardly moving vapour molecules is very small as can be gathered from Fig. 19. The stream lines are here so shown that the distance between the stream lines is proportional to the free molecular paths. One sees that those lines far apart in the upper part of the vapour spray for which the free molecular path in the upwardly directed part of the vapour spray is about fifty times as great as in the free molecular paths in the downwardly directed part of the vapour stream. As a result the air molecules easily pass in their flight in the direction of the punctuated arrows, *viâ* the upper part to the lower part of the vapour spray and from here are driven to the fore vacuum. The greater the emerging velocity of the vapour then the greater is the free path of the molecule in the upwardly directioned part of the vapour spray and the more quickly is the air aspirated into the vapour spray and so the better is the pumping action.

Here is the explanation of the distinctive phenomenon of the diffusion pump of the Langmuir type (Fig. 16) in that within wide limits, the pumping velocity is independent of the heating of the pump, and then with increased heating the emerging velocity of the vapour increases. In the first Gaede diffusion pump (Fig. 15) the velocity of the vapour was still so small that this effect could not occur, and the heating of the pump had to be exactly regulated.

The principal difference between injector and diffusion pumps are shown in the following effects; The vacuum which can be obtained depends with the injector pump on the total pressure in the vapour jet at F equally whether the jet consists only of vapour or if it is mixed with air. In the diffusion air pump the vacuum obtainable is not dependent on the total pressure of the vapour and air mixture at F, but dependent on the partial pressure of the air at F. If this partial pressure is zero then the vacuum obtainable is immeasurably high. This is related to the fact that the pumping velocity remains constant up to the highest degree of vacuum. If the vapour spray is mixed with air, or another gas, before it emerges from the jet then a high vacuum is no longer obtained

and the diffusion process no longer occurs,* as the gas pressure in the high vacuum is dependent upon the partial pressures of the gases in the vapour spray. With the injector pump the vacuum is excited dynamically by the weight of the vapour jet. In the diffusion pump, the high-vacuum excitation depends on the vapour stream rinsing out the air which diffuses from the exhausted vessel in a manner similar to that in which water rinses out dyed leather or coloured fibres, or as a solute diffuses out in a dialyser.

A diffusion pump during evacuation can at first act as an injector pump, as long as the air pressure is still great, corresponding to Fig. 18, given that the jet is so formed that a vapour jet occurs, which is not always the case. With further dilution of the air the vapour jet passes to a vapour spray and the type of stream-line picture then changes into the stream-line picture shown in Fig. 19 and the pump gives a high vacuum diffusion pump. Observations with the pump (Fig. 15), in which the physical relations clearly depend on the small vapour velocity, have shown that the pump acts with certainty as a diffusion pump when the product of the slit width in millimetres times the air pressure in millimetres of mercury equals, or is smaller, than 0·25. In the pump (Fig. 17) the slit width is usually in glass pumps 2·5 mm. so that the pump works from about 0·1 mm. of mercury down to the highest vacuum of the diffusion pump. If at the commencement of pumping the air is still greater than 1 mm. of mercury and the vapour jet is so constructed as to produce an injector, then at pressures above 1 mm. of mercury, the pump acts as an injector pump and so takes over the action of a fore pump. Between 1 mm. and 0·1 mm. of mercury the vapour jet goes over to a vapour spray and from 0·1 mm. downwards the pump works exclusively as a diffusion pump.

Of the numerous practical types of diffusion air pumps that have already been constructed and adapted to scientific laboratory and technical purposes we can only describe here the more recent forms in which the old diffusion air pump is reproduced. The material used in construction in modern diffusion pumps is either steel, glass or quartz.

## GLASS DIFFUSION PUMPS

The Langmuir † glass pump is shown in Fig. 20, but not in exact proportion. Mercury vapour is provided by an electrically heated boiler A and passes *viâ* B to the nozzle L, surrounded by a water cooling-jacket J, the condensed mercury vapour returning to A by M. The fore vacuum is applied *viâ* N and the fine vacuum vessel connected by R and F, a mercury trap G being inserted and cooled by liquid air or other suitable refrigerating agent.

* Molthan, *Zeits. f. Phys.*, 39, p. 1, 1926.

† J. Langmuir, *Phys. Rev.* (1), 6, pp. 48–51, 1916 ; *Gen. Elect. Rev.*, 12, 19, pp. 1060–1071, 1916 ; *Electrician*, 79, pp. 579–560, 1917.

For its operation it is essential that the jet L is below the level of water in the condenser jacket J and that the distance L to D is sufficiently great to prevent the reverse diffusion of gas. Otherwise the dimensions are largely immaterial and may vary upwards from an overall height of 4 in. only.

The Langmuir pump (Fig. 20) acts as already described in the schematic Fig. 16. The tube $D_1$ is here denoted by L, the diffusion slit *e* is here P, and the condensing surface is here C. The gas is drawn off as described in the case of Fig. 16.

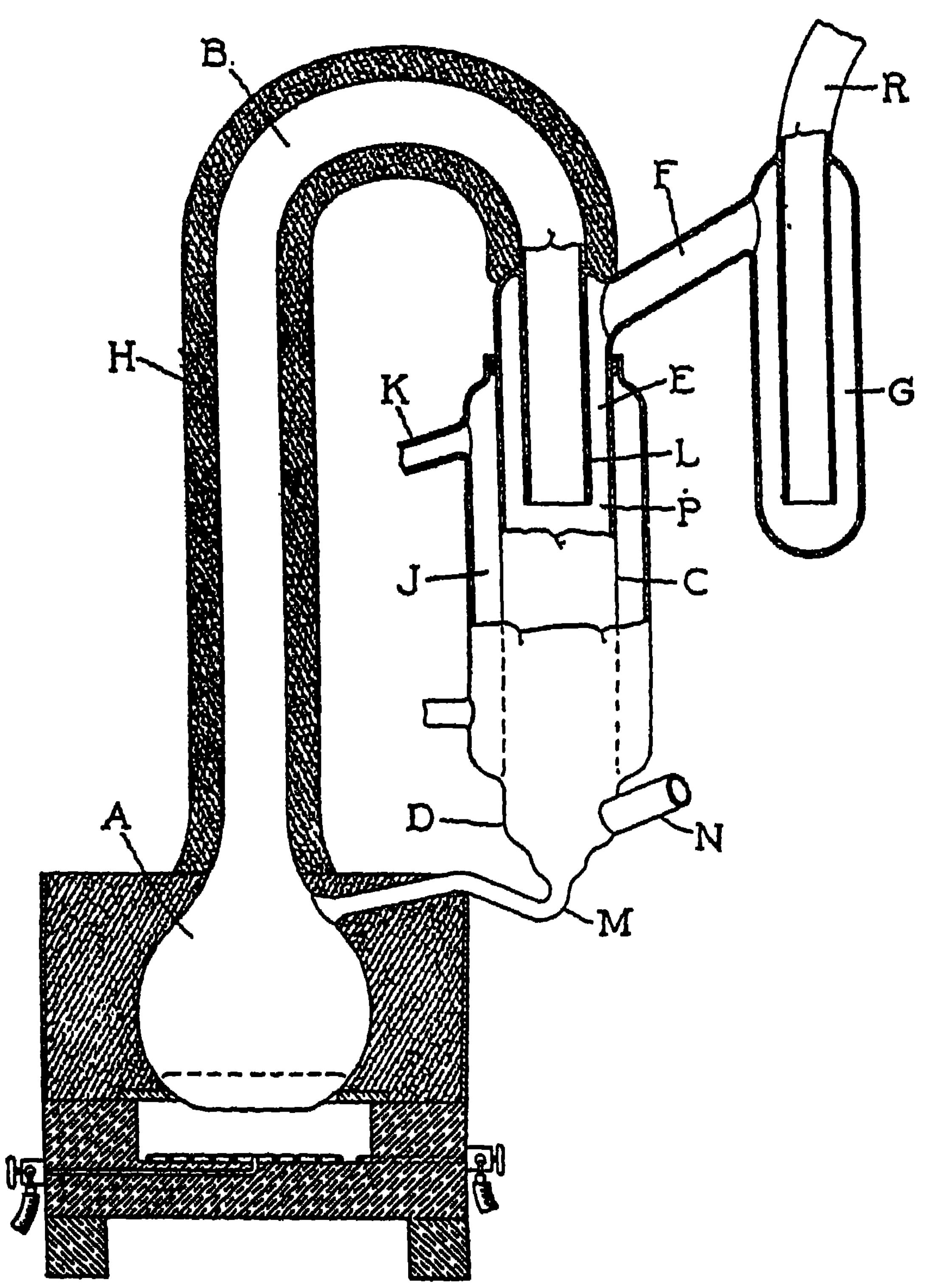



FIG. 20.—Langmuir Mercury Vapour Pump.

The Langmuir condensation pump is hence a particular case of the Gaede diffusion pump. In Gaede's original treatment * he shows that the volume of air V which diffuses into the blast of vapour causing evacuation is given by a complex equation which we can write more simply as $V = K_1 e^{-\frac{rP}{K_2}}$ where $K_1$ and $K_2$ are constants, *r* is the radius of the capillary tube *viâ* which the gas diffuses, and P is the gas pressure or a measure of the free mean path of the gas.

If the pressure P is large then, for a given value of V, *r* must be very small. Conversely if P is very small *r* may be very large, as the free mean path of the gas molecules is also very large.

In the original Gaede pump (Fig. 17) large values of P not necessarily requiring a fore pump were dealt with and *r* was therefore very small, Gaede in his theoretical treatment dealing with the case of the pores of a porous plug (Fig. 14) and using in practice a fine slit between steel jaws (Fig. 17).

If however we reduce the value of P by use of a fore pump then *r*

* *Ann. der Phys.*, 46, p. 373, 1915.

will become so large as to equal the diameter of the pump itself and the steel slit is no longer necessary, a fact shown by Williams and used by Langmuir.

The Langmuir pump is therefore a special case of the Gaede pump, but whereas the theoretical Gaede pump can by correct adjustment of the steel slit be used for all fore pressures, the non-slit type of pump of Williams or Langmuir cannot work at atmospheric fore pressures, a fore pump being essential.

Further glass pumps have been constructed by Gaede, Williams, Volmer, Schrader and Sherwood.* In a pump due to Gehrt,† of Siemens and Halske, the mercury is heated by forming a mercury arc itself. The mercury can be heated by other methods as direct heating, but with greater risk of fracture of the enclosing vessel.

The simplicity of operation of the mercury vapour pump should be recognised. The diffusion pump shares with the molecular pump the advantage that there is no limit of pressure except where the walls of the evacuated vessel evolve minute quantities of gases as fast as they are evacuated and a steady balanced condition of pressure thereby results.

With other forms of pump, which depend upon a definite fraction of the total volume of gas to be exhausted being shared with a volume of gas continually removed, there is necessarily no such lower pressure value since, however often these respective volumes are put into combination, some residual gas must always remain in the vessel being pumped.

## SILICA DIFFUSION PUMPS

An objection to glass mercury vapour pumps is the risk of fracture in the case of irregular heating and their general fragility, which they share with the glass X-ray tube.

The first objection has been overcome by the construction of pumps with Pyrex glass (Fig. 21) and with fused silica by Gaede (Fig. 22), Langmuir, Dauvillier and others. The quartz pump of Fig. 22 pumps in two stages: 3 is the high vacuum stage and excites the high vacuum by 8, 4 is the first stage and improves the fore vacuum of stage 3. The high vacuum stage 3, like the pump of Fig. 20, uses a fore vacuum of about 0·1 mm. of mercury. The fore stage 4 is made possible by use of a mechanical fore pump giving a vacuum of only about 10 mm.

Such silica pumps are far more resistant to sudden variations of temperature than glass and allow the use of higher temperatures to drive off air and other gases occluded upon the walls of the pump and its connections.

* *Phys. Rev.*, 12, p. 70, 1918.

† Gehrt, *Zeits, f. Phy.*, 1, p. 61, 1920; Brit. Patent 14,918/1915.

Whilst they are at the same time resistant to chemically active gases they are still extremely fragile to mechanical shock, particularly if employed in industrial processes.

## METAL DIFFUSION PUMPS

A metal vacuum pump has the advantage that it is mechanically rigid, strong, and is capable of easy dissembly for cleaning, etc. It suffers from the disadvantages that it is nearly impossible to prevent constant occlusion of gases from the walls and that it is liable to attack from chemically active gases as chlorine, etc., although if made of steel it is not attacked by the mercury vapour.

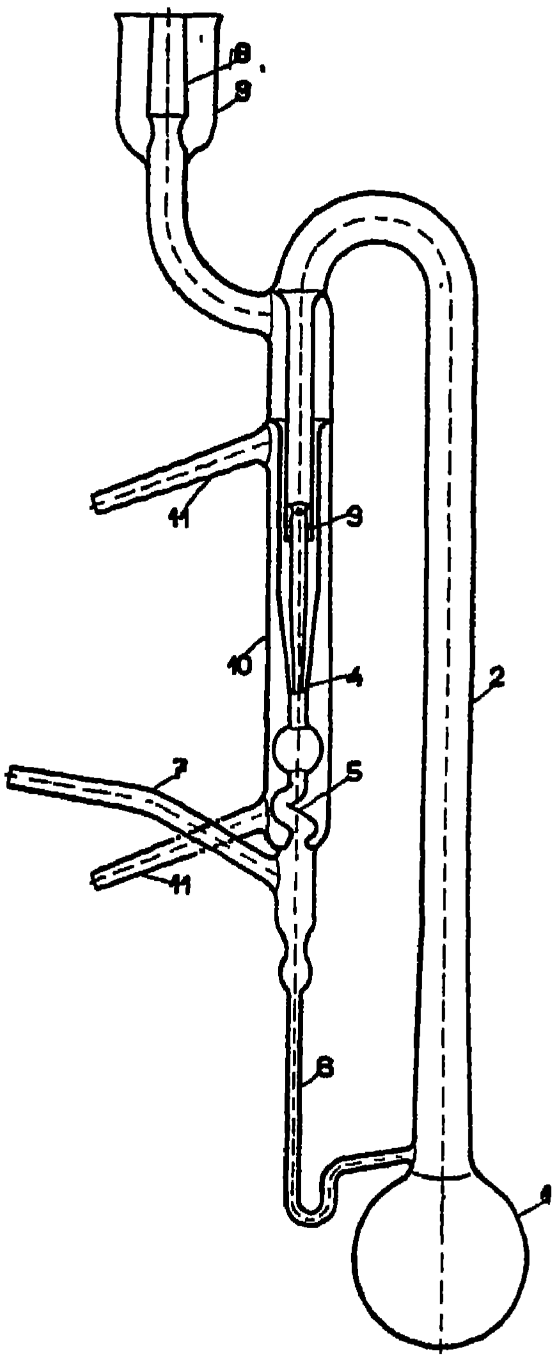



FIG. 22.—Mercury Vapour Pump of Silica (Messrs. Leybold).

The production of all-metal mercury vapour pumps is by no means recent. Gaede showed such a metallic pump in his paper of 1914. Fig. 24 shows a modern Gaede metal pump assembled with a Gaede oil pump. Such a combination provides an engineering apparatus rather than a physical laboratory apparatus. These metal pumps are made in one-stage, two-stage and three-stage types, *i.e.*, where the diffusion process occurs once, twice or thrice, so overcoming the need of three separate pumps.

The three-stage pump is shown in section in Fig. 25. This is built of steel and consists of a tube 18 and jacket 15 which are joined by flanges 8 and 36. The jacket is cooled *viâ* the water inlet 35 and outlet 5. A tube 14 below and 6 above opens into the tube 18 and *viâ* 7 is combined to the fore vacuum. The lower cylindrical mercury container 39 is bored and carries a flange 37. Flanges 36 and 37 are cemented and screwed together by bolts. The inner pump is a bored cylinder of iron and has partitions 25, 30 and 42 with vapour inlets 19, 22, and 28, and are all carried by a common steel rod 20. The spring 11 allows these to be inserted or removed from the cylinder and permits easy access to all internal parts.

The rough vacuum is applied at 7 and the fine vacuum is connected *viâ* 1. Mercury is heated in 47 and rises, *viâ* the inner tube 21, to diffuse *viâ* the cone 17 and to carry away gas entering at 1. The mercury vapour passes simultaneously *viâ* further jets 22 and 28. Condensed mercury returns to the boiler *viâ* 27, 38 and 46.

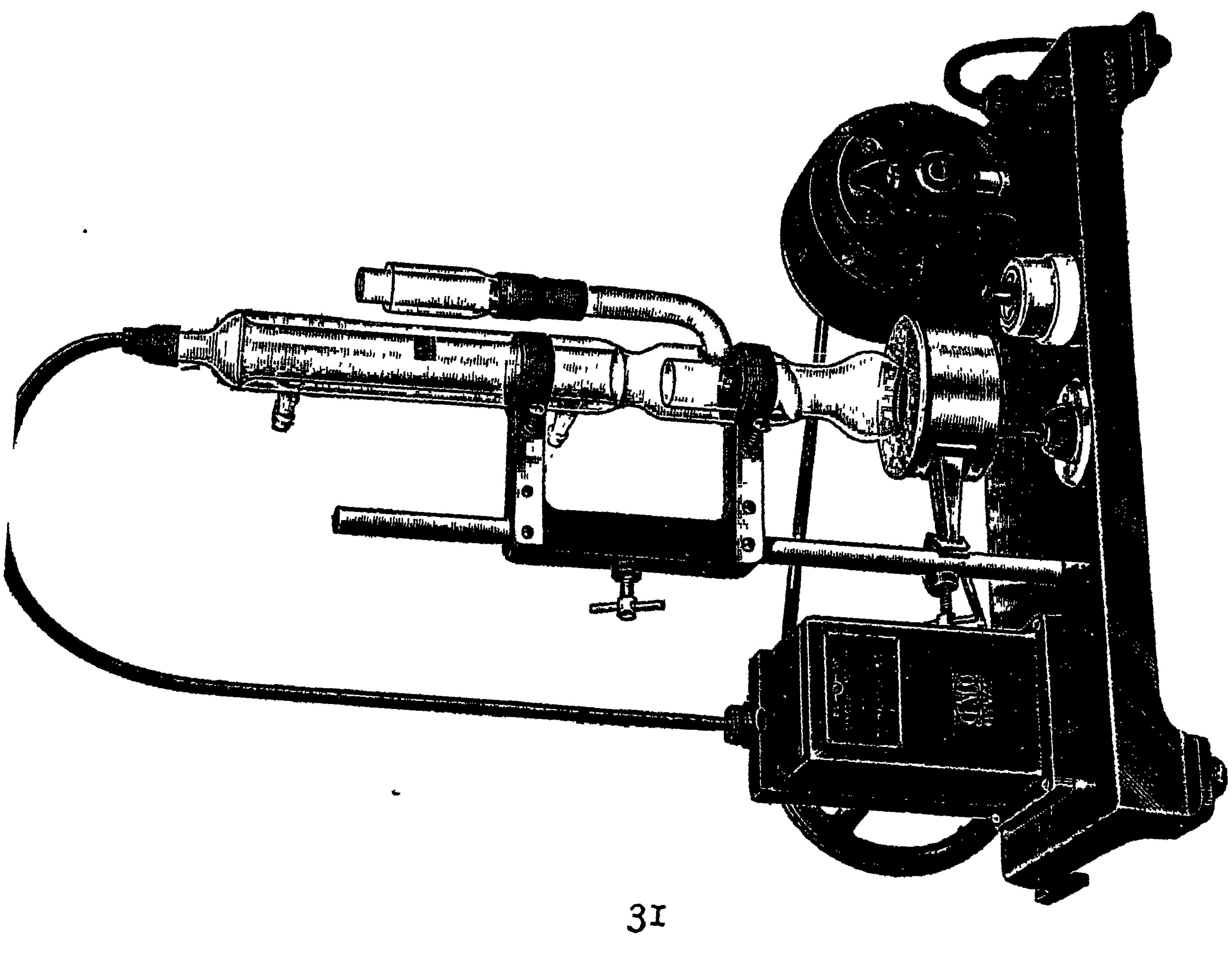


FIG. 21.—Pyrex Glass Mercury Vapour Pump with Oil Pump (Messrs. Central Scientific Company, New York).

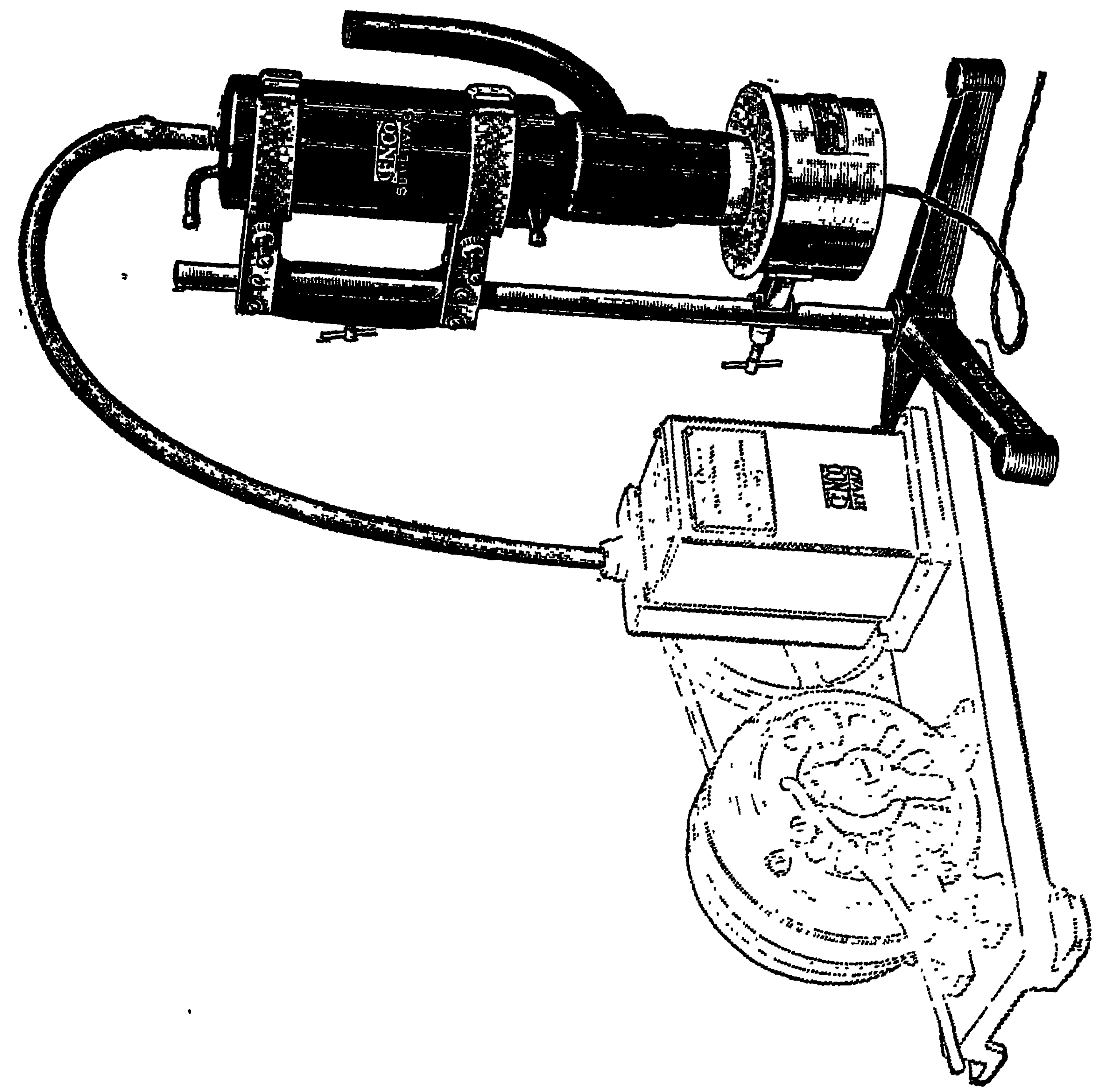


FIG. 23.—Metal Mercury Vapour Pump with Oil Pump (Messrs. Central Scientific Company, New York).

The lower two jets act as fore pumps and the upper jet as t. stage pump. A very high pumping speed is claimed for this pı being possible, at ·00001 mm. of mercury, to evacuate 60 litres of second, or 100 litres of more rapidly diffusing hydrogen. A pres low, that it can no longer be read by a Macleod gauge (*q.v.*), o. $10^{-6}$ mm. of mercury can be obtained. The fore vacuum is co tively high, namely 20 mm. of mercury. With such a fore vac

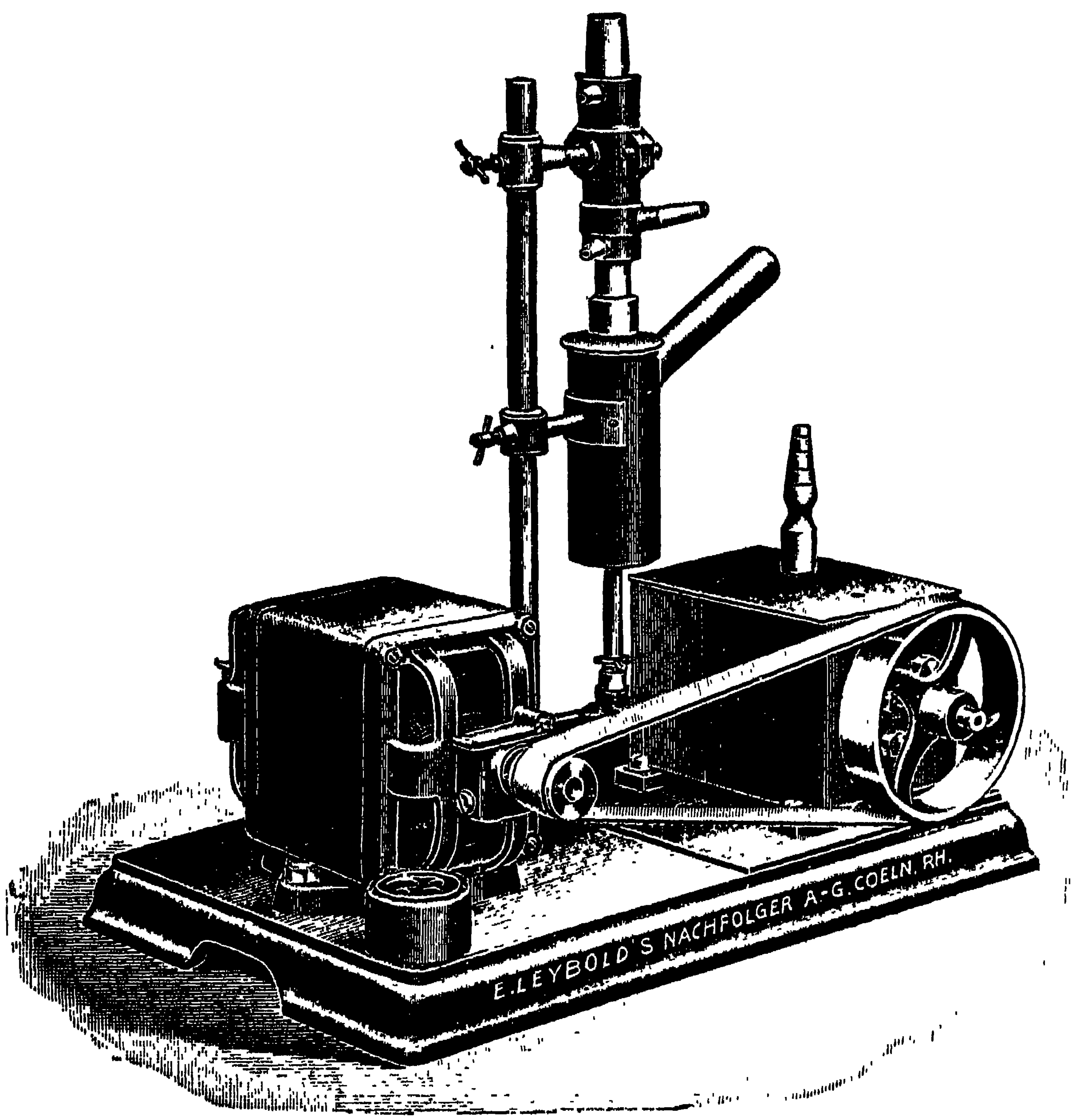



FIG. 24.—Motor-driven Oil Fore Pump and Metal Mercury Vapour Pump Coml. (Messrs. Leybold, Cologne).

20 mm. of mercury, the stages 19 and 22 correspond to a diffusion as Fig. 19. The lower stage 28, acts as an injector, correspondi Fig. 18.

Langmuir also built, about 1916, a metal mercury vapour characterised by its extreme simplicity. Mercury is heated in a D (Fig. 26) by electrical means and passes up a jet F, and after defl by a shield E draws gas from C by its passage downwards, the me

being cooled by the water jacket J. The rough vacuum is applied *viâ* B. Such pumps operate with a fore-vacuum pressure of below 10 bars and, for 300 watts energy consumption to heat the mercury, give a speed of 3,000–4,000 cm.$^3$/sec.

The specialised manufacture of high-vacua pumps has developed abroad rather than in England, notably by the firm of Leybold in Cologne and the Central Scientific Company in America. Other metal mercury vapour pumps have been described and commercially manufactured by Gaiffe, Gallot & Pilon of Paris. One of the few English pumps, due to Kaye,* may however be noticed.

Whilst this pump comprises no particular novel features either in its metallic construction or mode of operation, it being essentially similar to the single-stage Gaede metal pump, it is claimed it has the following practical advantages;

(1) High pumping speed.

(2) With a rough pressure of 1·5 mm. or less, the highest obtainable vacuum of $10^{-6}$ mm. of mercury, or less, can be produced. Higher values of rough pressure of 4 or 5 mm. of mercury are also applicable.

(3) Vapours or gases can be pumped.

(4) Wax or rubber joints are avoided by the use of steel-to-steel joints.

(5) No discharge of poisonous mercury vapour can occur.

(6) The pump is robust, light, easily dismantled, economical to run, readily portable, and noiseless, features common to all such metal pumps, such as the Gaede pump already described.

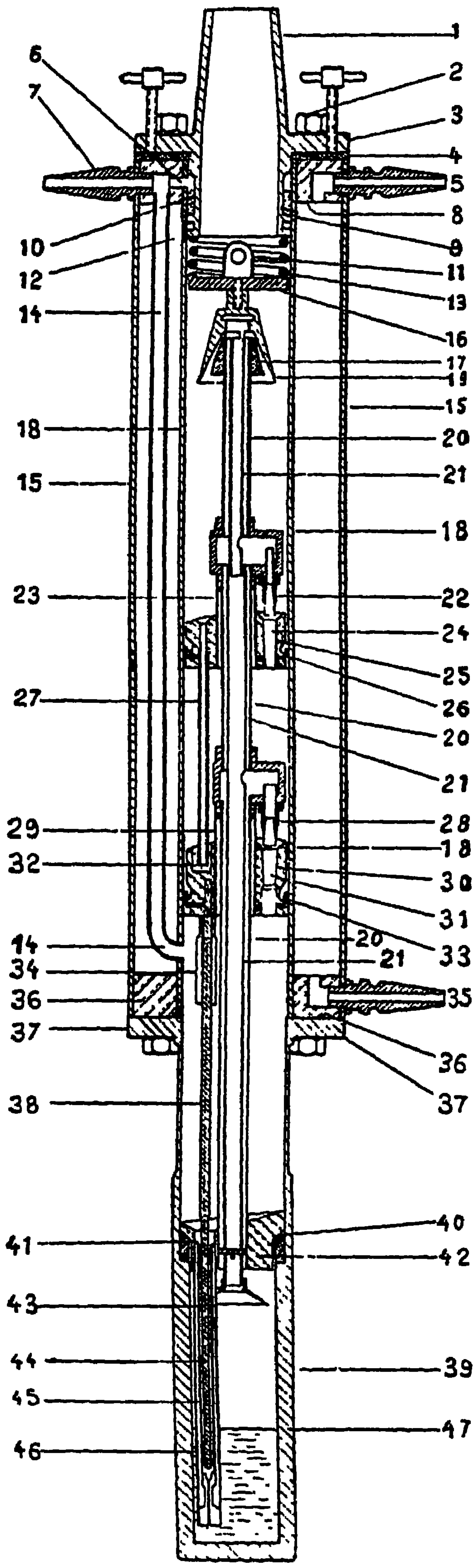


FIG. 25.—Gaede Three-stage Metal Mercury Vapour Pump (Messrs. Leybold, Cologne).

The pump is shown in section in Fig. 27, and is a one-stage pump. Mercury from the boiler passes up the central tube and then *viâ* an annular jet, so drawing air from the high vacuum, and is afterwards condensed by a water jacket, which is rendered more

* *Phil. Mag.*, p. 349, 1926; *and Brit. Journ. Rad.*, 22, p. 23, 1926.

efficient by a helix causing a swirling of the water around the inner wall of the water jacket. A needle valve is inserted to allow and to regulate air entry and pressure when the pump is used in conjunction with gas

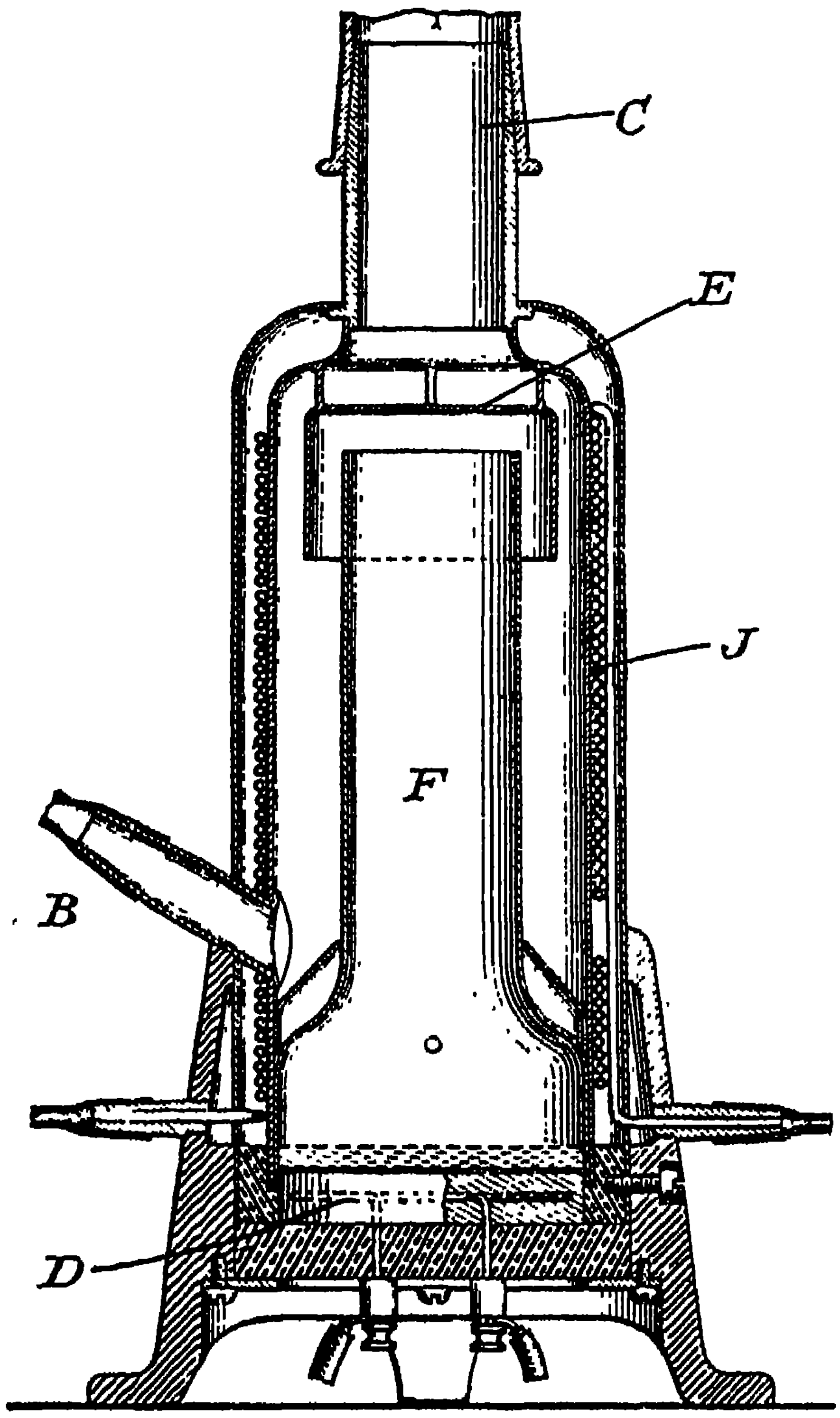



FIG. 26.—Langmuir Metal Mercury Vapour Pump.

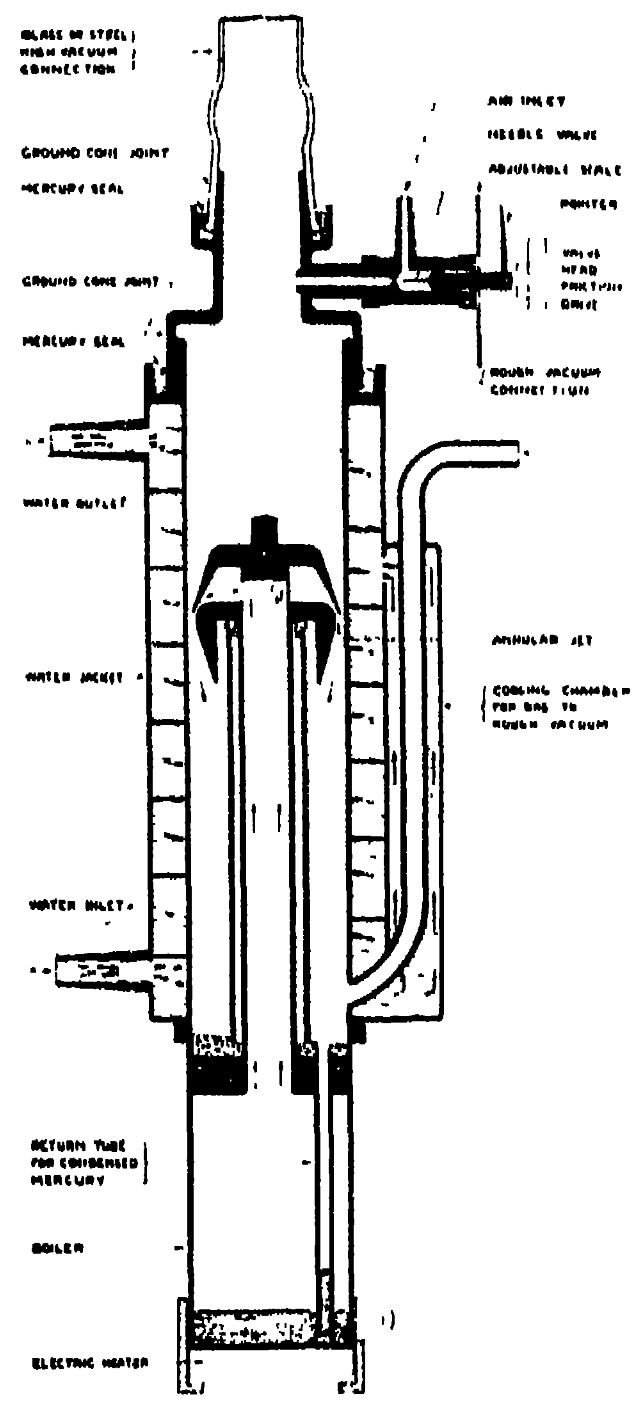


FIG. 27.—Kaye Metal Pump.

X-ray tubes in order to vary the hardness of such tubes at will, if too great a vacuum has been obtained. Electric or other heating is employed and the remaining features and details are obvious from the illustration.

A very useful table of vacuum pump progress is given by Kaye as follows regarding the pumping speeds of various pumps :

| | Speed cc./sec. |
|---|---|
| Sprengel and Töpler Pumps . | Very slow |
| Gaede Rotary Oil Pump . | 100—150 |
| „ „ Mercury Pump. | 100 |
| „ Diffusion Pump . . | 100 |
| „ Molecular Pump . . | 1,400 (max.) |
| Langmuir Condensation Pump | 3,000—4,000 |
| Kaye Metal Pump. . . | 7,000 (max.) |

I

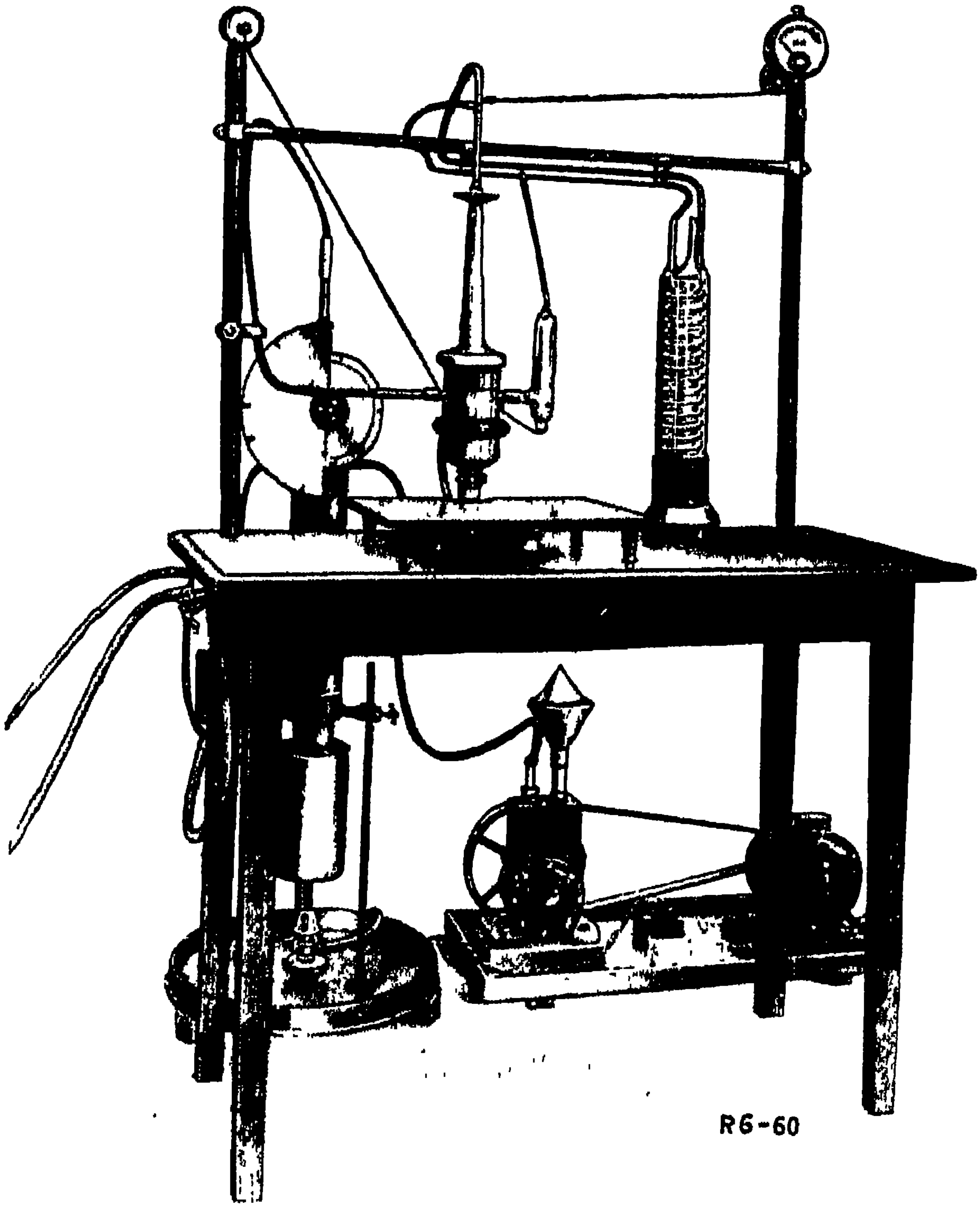



FIG. 28.—High vacua Plant (Messrs. Koch & Sterzel).

[To face p 35

Whilst the figures quoted tend to show the superior speed of this pump over the similar Langmuir pump (apparently the 1916 type) the diffusion pump of Gaede is obviously of the older slit type and not the modern type of Gaede pump just described, to which the single-stage Gaede pump is somewhat similar. With the three-stage Gaede pump on this same rating this would have a speed of 60,000 for air to 100,000 c.c./sec. for hydrogen and Kaye's claim of a very superior pumping speed can therefore hardly be maintained, irrespective of the very possible modern improvements in the Langmuir pump.

A typical evacuation bench for X-ray tube exhaustion for experimental purposes is shown in Fig. 28.

Beneath the table in the centre is a rotary oil pump driven by a motor to the right and producing a rough vacuum for the metal mercury vapour pump to the left, the heating burner for which is obvious. Upon the table in the middle is seen a metal X-ray tube of the Siegbahn type under exhaust, to the right a mercury vapour trap, and to the left a control needle valve for the mercury pump. The high-tension pillars (one carrying a milliamperemeter) for the excitation of the X-ray tube during exhaustion are obvious.

An important commercial application of high-vacua pumps is to maintain a high vacuum in mercury vapour rectifiers used for the purpose of converting high-tension alternating currents to direct high-tension currents. Since such a method of conversion of electrical energy is used for power purposes the high-vacuum plant, which comprises both oil and mercury vapour pumps, is necessarily large and a purely engineering apparatus capable of working with non-expert attention. An example of such a large mercury vapour pump is described in Appendix I.

## PHYSICAL AND CHEMICAL METHODS OF PRODUCING HIGH VACUA

Of these means of producing high vacua we have three distinct methods, namely;

(1) Physical adsorption methods.

(2) Chemical methods.

(3) Methods dependent upon gas ionisation.

The first two methods have little or no application in X-radiology technique, in comparison to direct pumping methods already described.

Of the physical methods the most important are adsorption methods by means of charcoal, or by metals, as platinum or palladium black.

*Adsorption by Charcoal.*—This method was introduced by Dewar in

1875 and, in consequence of the development of high-vacua pumps, has no application in radiology. It is chiefly used in physical processes but was also much used during the late War to adsorb poisonous gases in gas masks, and the knowledge of the basic physical phenomenon was greatly increased as a result of this application.

It is of X-ray interest that Paschen (Brit. Patent 10,878/1908) proposed to vary the vacuum or hardness of an X-ray tube by enclosing charcoal in an annexe of the tube and varying its temperature and consequent adsorption by heat to soften the tube, or by liquid air to harden the tube. Such a method has however not been used in comparison to other more convenient methods, since there is some risk of fracture of the tube envelope by the extremes of temperature, and liquid air is not a common agent in the normal X-ray clinical laboratory.

Dewar, to whom this high-vacua method is due, found that charcoal made from coconut wood was the most satisfactory, but that the adsorptive power varies with the particular portion of the nut used, *i.e.*, shell or true nut. The variations are doubtless due to the relative degree of porosity of the resulting carbon from these various portions of the nut.

The adsorption is also greater if the carbon is first allowed to adsorb gas and this is then driven off by reheating, the process being several times repeated. The adsorption also varies with the temperature and other conditions of carbonisation as well as upon the particular gas, a smaller volume of helium being adsorbed than hydrogen, under the same physical conditions.

The volume also varies as regards temperature of adsorption and is greater the lower the temperature at which the charcoal is maintained. For this reason Dewar worked at very low temperatures by means of baths of liquid air and, with such baths, very low pressures can be obtained by use of charcoal, for example, a 2,000-c.c. bulb in liquid air is reduced by 20 gr. of charcoal to a pressure of ·00025 mm. of mercury.

To explain this adsorption phenomenon, Langmuir has advocated a theory based upon residual chemical valency as the cause of the gas being held by the charcoal or rather, as the cause of a balanced absorption and dissociation in the steady state, when gas is continually being attracted to the adsorptive material and is continually given off, the balance of gas held being dependent upon the physical conditions as pressure and temperature.

Whilst this view is very ingenious it is not yet generally accepted.

*Adsorption by Platinum and Palladium.*—The pressure of a gas-containing vessel may be greatly lowered by means of platinum black, a finely divided form of platinum that not only adsorbs large quantities of gas, so reducing the surrounding pressure, but also acts as a chemical catalyst to cause chemical reactions, for example, hydrogen and oxygen

will combine with great violence to produce water. Such catalytic reactions of platinum have been used in the commercial production of chemicals and particularly sulphuric acid.

Palladium, related chemically to platinum, has also this property both in the finely divided black form and in metallic form. This property is much improved in value if the palladium as heated and is used in the well-known osmosis X-ray tube regulator of Villard (see p. 80). When heated the metallic palladium becomes pervious to gases, the most probable explanation being that the gas enters into a state of solution in the metal and so passes from the external atmosphere to the internal atmosphere to the tube.

By adsorption with palladium pressures as low as ·0001 bar have been obtained. This method of obtaining high vacua has been actually used in the manufacture of " Kenotron " valve-tube rectifiers, until given up in favour of the cheaper charcoal adsorber, inferior however in adsorptive power. For good adsorption the mode of preparation is, as with charcoal black, very important, to produce an " active " variety which gradually loses its activity.

*Chemical Methods.*—It is obvious that if a chemical reaction can be produced between gases, or a gas and a solid, to produce a non-vaporising solid compound the consequent removal of the gas will cause a lowering of the gas pressure.

The first use of such a chemical process was utilised in 1894 by Malignami, in the very early days of electric lamp manufacture. It was found that if phosphorus was ignited by heat, or electrically, in an incandescent electric lamp bulb, the life of the lamp was greatly increased, the oxidation of the carbon filament of this date being so prevented by removal of the oxygen as phosphoric oxide.

Other than purely chemical reactions, which remove oxygen as oxides and nitrogen as nitrides, it has been suggested that the residual gas is also probably ionised and, being attracted by the bulb walls by electrostatic attraction, is held to the walls by a deposited condensed film of the vaporised material, known in lamp technology as a " getter."

A perusal of the patent literature shows that, whilst the most common practical " getter " is still phosphorus or magnesium, nearly every other element has been used, or at least patented as a " getter," for example, calcium, barium and strontium (originally used by Soddy in 1907), thorium, zirconium, iodine, sulphur, titanium, magnesium, arsenic, niobinium, vanadium, boron, cermium, cæsanium, hafnium, lanthinium, and lime, and one may state that every metal of the rare earths has been suggested as a " getter," a well-known example of which is " misch metal " a cerium-lathinium alloy.

Langmuir has extensively studied the action of a heated tungsten filament in removing residual gas. It is found that this metal, by

chemical combination, will remove oxygen, nitrogen, hydrogen, carbon monoxide, carbon dioxide, chlorine, bromine, iodine, methane and cyanogen, *i.e.*, all the gases usually present during exhaustion, with the exception of the inert group of gases, and such absorption has been used of recent years to separate such inert gases.

This method of gaseous absorption has been used to maintain the vacua of highly exhausted electron X-ray tubes by the enclosure of a suitable "getter" in an annexe to the X-ray tube (Brit. Patent 109,358/1916). It must also act to remove such gases when tungsten is sputtered from the target of an X-ray tube and particularly in a gas tube having a tungsten target, the residual gas of which is air.

*Reduction of Pressure by Electrical Discharge.*—The gradual hardening of all electrical discharge tubes was first observed by Plückner in 1858 and is a well-known occurrence to all medical radiologists.

Whilst there is no question as to this fact, there is considerable disagreement as to the exact phenomena responsible for this hardening. All theories fall however into either chemical processes or physical occlusion.

In the chemical processes which operate it is possible that chemical reactions, resulting in the removal of gas from the tube atmosphere, may occur with ;

(1) the glass wall,

(2) the anode,

(3) the cathode,

(4) by the combination of other gases with an active form of nitrogen.

All these combinations have been advocated as the prime cause at various periods.

Similarly, in occlusion theories, the hardening has been attributed to occlusion of gas by ;

(1) the glass walls,

(2) the cathode,

(3) the disintegration of the anode and adsorption by the metal sputtered from the anode.

Amongst all these various possible causes it is nearly impossible to determine the effect of any particular cause, and doubtless the hardening is the result of several such causes.

*Chemical Theories.*—Willows * has advocated that the hardening is chiefly due to the glass walls. As a basis of this view is the fact that the particular composition of the glass undoubtedly plays a part, since Willows found the adsorption to vary with Jena, lead and soda glass, in the order given with smallest adsorption by Jena glass. These results would tend to show, for most steady operation, an X-ray tube is best constructed of Jena glass, whereas the more usual soda glass has greatest

* *Phil. Mag.*, 6, p. 503 (1901).

effect. It is stated that glass does not adsorb gases unless it is repeatedly conditioned by discharge when filled with hydrogen.

Skinner * has shown that gas is evolved at the cathode and absorbed at the anode, the process appearing to follow the laws of liquid electrolysis, *i.e.*, the passage of 96,500 coulombs giving rise to the emission of 1 gr. of hydrogen at the cathode which is absorbed by the anode. Christler † has also suggested absorption at the anode as playing a large part in the hardening process.

Mey ‡ and also Newman § have, from other experiments, concluded the basic cause is due to chemical combination of the gas with the cathode. Strutt || has shown that nitrogen which is subjected to an electrical discharge attains a greater degree of chemical activity. Dushman ¶ has pointed out that by virtue of the great velocities attained by gas ions in the X-ray tube, these ions have energies comparable to the intrinsic energies of atoms when raised to high temperatures. Since most chemical reactions are facilitated by increased and high temperatures, it is reasonable to suppose that atoms taking part in gaseous discharge may, by virtue of their increased energies, have much more potent chemical actions.

*Occlusion Theories.*—Early in the history of X-radiology Campbell Swinton advocated that gas is removed from an X-ray tube by occlusion upon the walls of the tube. Such a view is consistent with the well-known fact that a tube may be temporarily softened by heating its walls in a sand bath. On the other hand such a practical result would be consistent with the chemical view of absorption if we suppose the chemical compounds, formed by the removal of gas, are broken down by the applied heat, particularly since such softening is only temporarily, and we may regard the disintegration products to remain chemically nascent, so rapidly recombining after removal of the heating medium.

Against such a chemical view and in favour of the physical adsorption view, is the fact that non-chemically active gases as helium and argon are also removed from the tube atmosphere and, since all means at our disposal have failed to cause chemical reaction with such gases, it is very improbable that they are removed by chemical combination with the tube walls or electrodes.

Ramsay and Collie ** have shown the presence of helium and neon in the glass of old X-ray tubes and Goldsmith has shown that high-speed canal rays of hydrogen and helium can penetrate depths of mica up to ·006 mm. in the same way that the high-speed $\alpha$ particles of radium can penetrate glass.

* *Phil. Mag.*, 12, p. 481 (1906).
† *Phys. Zeits.*, 10, p. 745 (1909).
‡ *Ann. d. Phys.*, 11, p. 127 (1903).
§ *Phil. Mag.*, 44, p. 215 (1922); *Proc. Roy. Soc.*, 90, p. 499 (1914), 32, p. 190 (1920); 33, p. 73 (1921).
|| *Proc. Roy. Soc.*, 85, p. 219 (1911).
¶ *Gen. Elect. Rev.*, 34, p. 441 (1921).
** *Nature*, 89, p. 502 (1912).

Such facts would indicate the possibility of the hardening of an X-ray tube being due to gas ions being actually driven into the tube wall in consequence of their high velocities and, being entrapped in the glass. The result is a gradual decrease of pressure in the tube, due to loss of such ions. Indeed views have been expressed that such ions are driven completely through the glass tube wall. Such views are most likely erroneous, as enormous energy values would be necessary to drive such ions through a tube wall of say 1 mm. thickness, *i.e.*, $\frac{1}{.006}$ times, the distances observed with high potential canal rays. Coolidge has however recently * obtained such canal rays by the use of 200 kv. and above, at large distances from the vacuum tube, and the possibility of complete passage, by rapid increase of penetrating power with increase of voltage, should not be lost to view.

Riecke † has attributed the hardening to occlusion at the cathode. A similar action at the target is unlikely, in view of the high temperature this electrode often obtains, which undoubtedly favours emission rather than adsorption of gas. Rapid softening of an X-ray tube is well known to result by overheating the anode.

Campbell Swinton and others observed, when the glass of old X-ray tubes was heated, that bubbles of gas were evolved which were attributed to the release of gas previously driven into the glass. The experiments of Ramsay and Collie appeared to support this view. Soddy and Mackenzie,‡ working with discharges *viâ* rare gases, dispute, when gas is evolved from the containing discharge tubes on heating, that any trace of such rare gases can be obtained, the resulting bubbles of gas being merely due to decomposition of the glass chemicals under ionic bombardment, and similar bubbles may be obtained by decomposition, on heating, of glass which has not been subjected to such discharges. Quartz glass likewise gives such decomposition gases by ionic bombardment.

Soddy and Mackenzie § and also Hodgson and Brodetsky || have suggested that the hardening of a discharge tube is due to mechanical adsorption of gas by finely divided particles sputtered, or driven off the cathode, by ionic impact. This view is based upon the fact that finely divided metals as platinum and palladium, often used as X-ray tube targets, are, in the finely divided state, as already mentioned, greatly prone to gas adsorption. It is well known that the bulb of an X-ray tube after long use becomes coated in its interior with such potent adsorptive metal, and the softening by heating a tube bulb, may be due to this adsorbed gas being temporarily driven off from the sputtered metal, which re-adsorbs the gas on cooling.

* *Jour. Franklin Inst.*, 202, p. 693 (1926).
† *Ann. d. Phys.*, 15, p. 1003 (1904).
‡ *Proc. Phys. Soc.*, 35 (1912).
§ *Proc. Roy. Soc.*, 80, p. 92 (1908).
|| *Proc. Roy. Soc.*, 80, p. 92 (1908).

It should be also recollected that such finely divided metal can act as a catalyst and may be the cause of chemical reactions between the gases within the tube, for example, in a tube pumped from air, the oxygen and nitrogen may under the action of such a catalyst be combined to form acid nitric oxides which then react with the alkalis of the glass and form solid nitrates so removing the above gases from the tube atmosphere. A final view of the increase of vacuum by discharge is that the residual gas is removed from the sphere of operation in much the same way that water vapour is removed by electrons and ions in the well-known C. T. R. Wilson condensation experiment (*q.v.*). Hence the gas atoms may act as nuclei upon which electrons and ions impart a charge and these charged atoms are then attracted by the oppositively charged portions of the tube wall and electrodes and so removed. This view appears to be upheld by the view of the action of phosphorus and other "getters" in the "clean-up" of electric lamp manufacture, already mentioned. The gas so attracted and held to the tube walls would not be disengaged unless additional energy were applied in the form of heat. It is well known that such ionic bombardment of the walls play a large and fluctuating part in the production of electrons for the passage of the discharge.

## THE MEASUREMENT OF LOW GASEOUS PRESSURES

An increasing variety of methods are available for the measurement of low gaseous pressures, many of which are purely comparative methods, rather than absolute methods of measurements.

The most common methods are ;—

(1) Mechanical methods.

(2) Methods based upon direct measurement of the movement of mercury levels.

(3) Methods based upon Boyle's Law (Macleod gauge).

(4) Radiometer methods (Knudsen).

(5) Methods based upon the conduction of heat *viâ* gases (Pirani-Hale).

(6) Methods based upon gas ionisation.

(7) Methods based upon the phenomenon of gas viscosity.

Up to the moment the most frequently used method is the second, in the form of the Macleod gauge, but of recent years the radiometric, and particularly in commercial processes, the ionisation methods have received extended application.

(1) *Mechanical Methods.*—The most important of these methods is due to Scheele and Heuse, in which the slight movement of a thin copper

membrane is measured, having one side subjected to a standard pressure and the other side to the unknown pressure. The minute variations of the diaphragm were measured by optical interference methods and pressures up to ·0001 mm. of mercury could be read. The results were however impaired by the fine vacuum being affected by the gases occluded from the walls of the metal diaphragm.

(2) *Methods Based upon the Direct Measurement of Mercury Levels.*—The direct reading of a mercury manometer can be measured for pressures ranging as low as 1 mm., but for measurement below this, exceptional experimental error and difficulties arise. The best known gauge of this type is that of Schrader and Sherwood (Fig. 29) which allows pressures as low as $10^{-3}$ mm. of mercury to be measured directly.

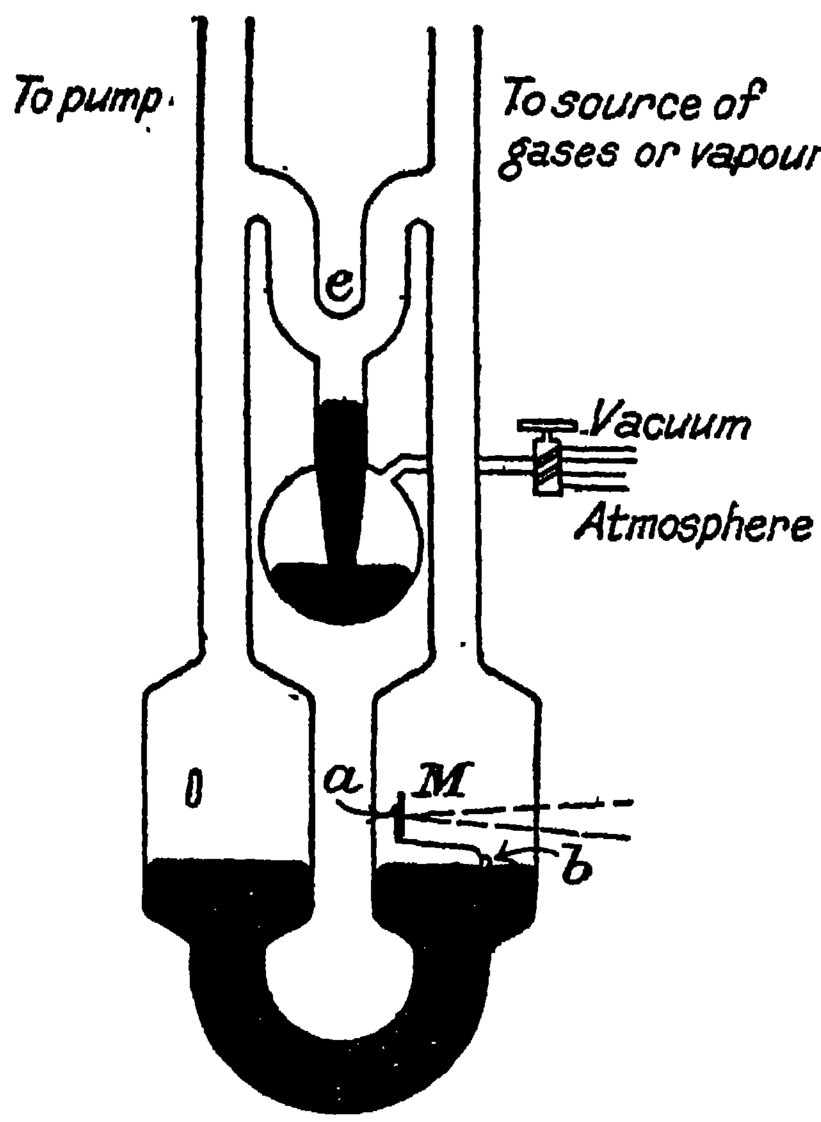



FIG. 29.—Schrader and Sherwood Gauge.

To avoid errors, due to capillary effects, a large U-tube is used, and upon one surface a glass bead *b* is floated, which actuates a lever pivoted upon two knife edges *a*. Upon this lever is a small mirror M from which light is reflected, so giving an inertialess optical lever, which, if of sufficient length, gives for a small displacement of the mercury level, a measurable reading of the displacement of the light beam. For pressures lower than the limit mentioned, errors arise due to variations of surface tension, very dependent upon the cleanliness of the mercury and glass, temperature effects, etc.

(3) *Methods Based on Boyle's Law.—The Macleod Gauge.*—This is the simplest and most widely used gauge and is based upon the assumption that Boyle's Law is accurately obeyed at the low pressures measured. Such an assumption cannot be directly made since it is well known that the corresponding law of variation of pressure with gas temperature is not obeyed at low temperatures.

The Macleod gauge (Fig. 30) is very simple in operation. A tube E, from the vacuous space the pressure of which is to be measured, is led to a bulb V of several hundred (usually 500 c.c.) cubic centimetre capacity, above which is a fine-bore capillary tube *aa*. When the vessel B is raised the vessel V is cut off from the vacuum, when the pressures in E and V are equal. Further raising of the vessel B then compresses the gas in V

until it is entirely within the capillary tube *aa* of known volume. Pressure and volume of the compressed gas being known, the original pressure of the gas in the bulb V and capillary tube *aa* of volume *v*, when in communication with E, can be obtained from the Boyle's Law relation, $P \times V =$ constant, corrections being made for temperature.

To ensure accuracy, by avoidance of experimental errors, various refinements are introduced in the actual gauge. One such refinement is the use of a side tube *bb*, as shown, of similar bore, which allows direct comparison of the levels of the compressed gas in the capillary tube and in the practically non-compressed gas of the vacuous vessel, to avoid errors of mercury curvature, etc. Whilst the method is simple it does not lend itself to automatic registration as in the case of other methods. It is also tedious, since it is necessary to allow time to elapse before readings, to ensure that the final level of the mercury level, delayed by capillary effects in the narrow tube, is attained. Such capillary effects ultimately limit the fineness of the bore of the tube *aa* which can be practically used and the ultimate accuracy of the gauge. With various refinements such gauges will read accurately to ·01 bar (·00007 mm. of mercury), or below the limit of electron X-ray tube evacuation.

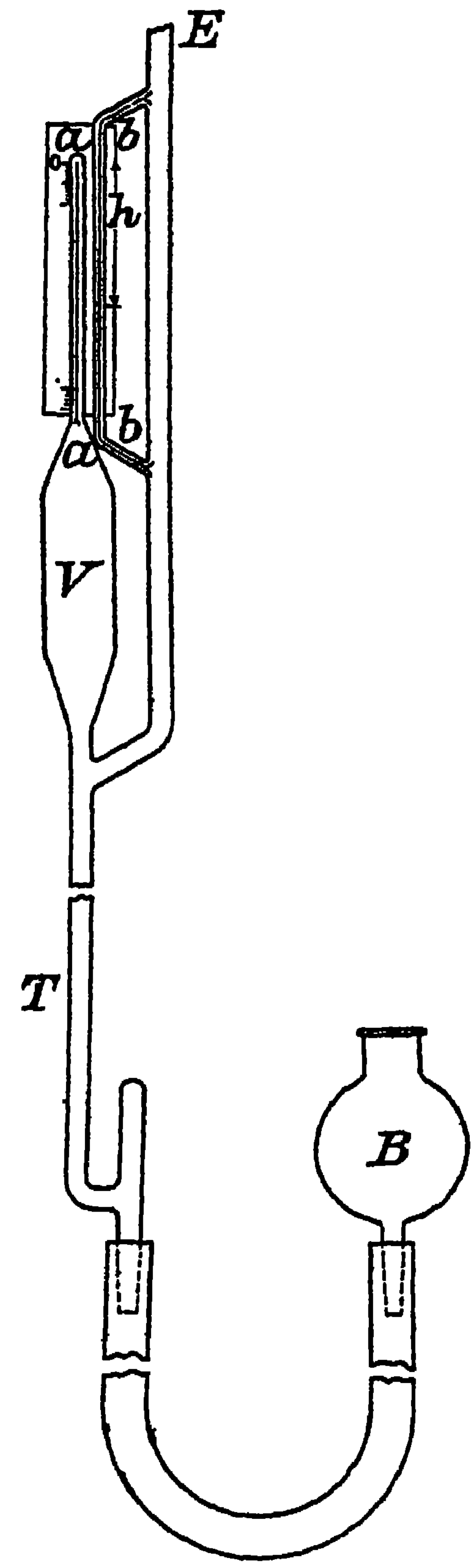


FIG. 30.—Macleod Gauge.

A practical type of Macleod gauge is described in detail in the Appendix to Chapter I.

(4) *Radiometric Methods.*—Fresnel demonstrated that in a rarefied gas a force was exerted between two surfaces at unequal temperatures.

This early discovery was the basis of the Crookes radiometer, often seen in opticians' windows, in which sunlight, falling upon a system of pivoted light metallic vanes, having alternate polished and blackened surfaces, causes the rotation of the pivoted system.

This phenomenon was studied at very low pressures by Knudsen, to whom we owe much of the theory of high-vacua measurement, and applied by him in a gauge commonly known as Knudsen's Absolute Gauge.

It is capable of proof that the mechanical force between surfaces of unequal temperature is related in terms of the absolute scale temperatures of the surfaces and the pressure of the gas between them.

Actually this pressure is due to a gas molecule, impinging upon a particular heated surface, having its temperature raised to that of the surface and thereby having its kinetic energy of movement increased.

If a hot and a cold surface are situated at a distance comparable to the dimensions of the " free mean path " of the gas molecule, which at low pressures in relatively large, then all molecules, on impact with the hot surface, will have greater kinetic energy due to greater velocities, than those molecules impacting upon the cold surface.

If, after impact, these molecules, or a certain proportion of them, pass from surface to surface, those molecules passing from hot to the cold surface will have greater energies than those passing from the cold to the hot surface.

If $T_1$ is the absolute temperature of the hot surface and $T_2$ of the cold surface, due to this inequality of molecular kinetic energies, when these molecules again impact with the opposite surface, the energy given up at $T_2$ will be greater than at $T_1$. The result will therefore be a difference of gas pressure upon $T_1$ and $T_2$ directioned from hot to cold surface and proportional both to the absolute temperatures upon which the kinetic energy of any molecule depends and to the gas pressure, which measures the number of gas molecules and impacts.

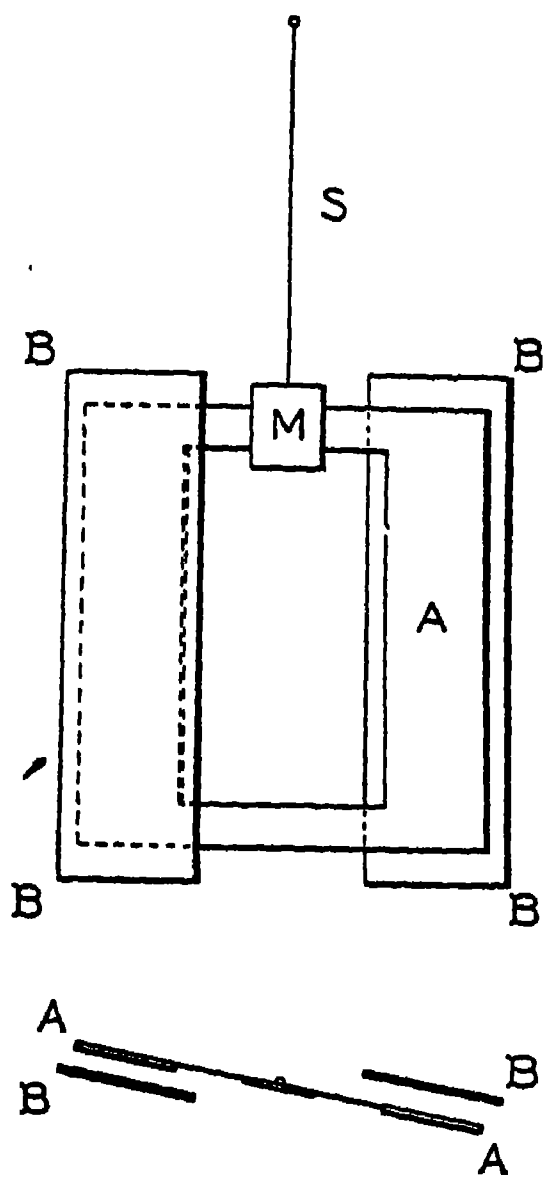


Fig. 31.—Knudsen Gauge.

If we can measure the value of this mechanical force then, since it is dependent upon the number of molecules, *i.e.*, the gas pressure, we have a method of determining gas pressures by this phenomenon.

To apply the effect to practical purposes Knudsen suspended a light vane of mica AA (Fig. 31) by a quartz fibre S, in the interior of a large tube, in which two plates of glass or metal B, are fixed and can be heated to desired temperatures by direct radiation from the side of the tube, if glass, or by electrical means, if metal. As a difference of temperature may so be caused to occur between A and B an attraction or repulsion of the vane will occur, according as to whether A or B is of higher or lower temperature. As a result the vane AA experiences a mechanical force or couple, tending to cause its rotation under control of the suspending quartz fibre S, and this force, with given temperatures of the surfaces, is proportional to the surrounding gas pressure. If therefore the movement of the vane is measured by means of the reflection of light from a mirror M upon it, we are in a position to measure gas pressures by such an instrument, an example of which is shown in plan and elevation in Fig. 31.

Since the movement of such a gauge can be expressed in measurable physical quantities as temperature, quartz-fibre torsion, mass of the

molecules,* etc., it is unnecessary to calibrate this gauge in terms of another type of gas gauge and absolute pressure determinations can be made not, as in the Macleod gauge, dependent upon the validity of Boyle's Law. In view of such definite measurement being possible this gauge has received the name of " absolute " gauge.

Various modifications of this gauge have been introduced to ensure accuracy by Knudsen and others and notably by Woodrow, Schrader and Sherwood and, since pressures as low as the order of $10^{-9}$ mm. of mercury can be measured, it is probably the most fine and accurate method of low-vacua measurement yet devised, as well as exemplifying one of the most complete and accurate applications of modern molecular physics.

Since the radiometer action is not exhibited at high gas pressures, as the molecular free path is not then sufficient to allow direct passage of molecules from surface to surface (the energy of the heated molecules being then frittered away to other gas molecules by impact) this gauge is only suitable to measure low and not high gas pressures.

Again at very extreme gas pressures the effects is dependent upon the use of a large temperature difference or a very light pivoted vane of low mechanical inertia, as otherwise the number of molecules are so few as to be unable to impart sufficient energy to the vanes to cause motion.

The radiometric method of measuring pressure does not appear to be used in purely technological high-vacua operations, doubtless owing to its extreme sensitiveness only rendering it suitable for refined physical methods of use.

(5) *Methods Based upon Gaseous Conduction.*—This method was first applied by Pirani for practical vacua measurements in the lamp factory of Siemens and Halske. Subsequently the method was rendered suitable for refined measurements by Hale, who claims a sensitivity of ·00001 mm. of mercury, or ·0133 bar.

It was observed by Pirani and others that the resistance of an electric lamp varied with the degree of exhaustion. Measurement of this resistance therefore allows, after calibration, a measurement of the degree of vacuum.

The underlying phenomenon is that, at low gaseous pressures, the gas molecules have a sufficiently long free mean path to be able to pass directly from the heated lamp filament to the walls of the bulb. Such molecules can therefore transfer heat from the incandescent filament to the colder walls of the bulb, where heat is conducted *viâ* the glass and removed by external air convection currents. Since the electrical resistance of a wire or filament varies as its temperature, such resistance will vary with the rate at which heat is conducted away from the filament both by direct radiation and gaseous conduction.

Actually the resistance varies until a steady state is obtained, at

* The vane movement is dependent upon the mass of the molecule and therefore the kind of gas.

which heat is lost at the same rate as heat is developed by virtue of its electrical resistance, providing change of state of the filament does not previously occur.

The greater the pressure of the surrounding vacuum, *i.e.*, the greater the number of conducting molecules, the greater is the heat loss, for a given energy input to the filament, and the less the resistance.

To apply this method Pirani used a normal electric lamp the bulb of which was in connection with the vacuum to be measured and the filament maintained below incandescence. Measurements of resistance variation were made by means of a Wheatstone bridge galvanometer connection.

The later, more accurate, Hale gauge is essentially an electric bulb of very accurate standardised design, in a Wheatstone bridge, with a similar compensating lamp at a given pressure in the opposite arm of the bridge.

(6) *Measurements Based upon Gaseous Ionisation.*—For these measurements an ordinary wireless three-electrode (triode) valve is applicable. The action of such valves has been already discussed (Chapter VI., Vol. I.).

An electron current from filament to plate is furnished by a thermionic tungsten filament, or a coated Wehnelt cathode.

These electrons are accelerated by the potential between filament and plate and their velocities are capable of modification, in order to vary the sensitiveness, by the potential difference between grid electrode and filament.

If the valve is very highly exhausted a definite relation exists between filament temperature and plate current, which is capable of mathematical representation.

If however gas is present, the electrons, furnished by the filament will, if given a definite velocity, by means of the filament-plate potential, acquire sufficient kinetic energy to ionise the residual gas, which thereby gives an increased number of electrons and therefore an increase filament to plate current.

It follows that the extent of this ionisation must be dependent upon the number of ionising collisions with gas molecules, therefore upon their number per unit volume and therefore the gas pressure, the greater the pressure within limits, the greater the ionisation and the greater the filament-plate current.

A measurement of this current by means of a suitable milliamperemeter in the plate circuit, allows a relative measure of the gas pressure within the triode bulb, and if connection is made between this bulb and the vacuum to be measured, a measure of this vacuum is so obtained.

This current and pressure relation will vary with the nature of the gas, since the ionisation voltage varies with the particular gas (25 volts for helium). Such measurements are purely comparative, but have great application in commercial lamp and X-ray tube evacuation processes.

For absolute measurements the ionisation gauge must be calibrated in terms of a standard gauge or by a method described later.

A sensitivity of $10^{-6}$ mm. of mercury is easily obtained by this method.

(7) *Methods Based upon the Viscosity of Gases.*—The subject of gas viscosity has been briefly dealt with, in describing the molecular type of vacuum pump, when it was stated that at low gaseous pressures a moving body dragged gas in its own direction of motion.

It follows that if in an evacuated space a body is given a certain motion, part of the energy applied will be expended in giving kinetic energy to the molecules of gas which it drags in the same direction. To maintain a velocity equal to that which would occur in a perfect vacuum, necessitates the application of additional energy, in order to overcome this frictional loss due to the gas viscosity. Conversely for any given applied energy the velocity will be decreased by the viscosity effect, by a value dependent upon the number of gas molecules set into motion and this will be dependent upon the gas pressure.

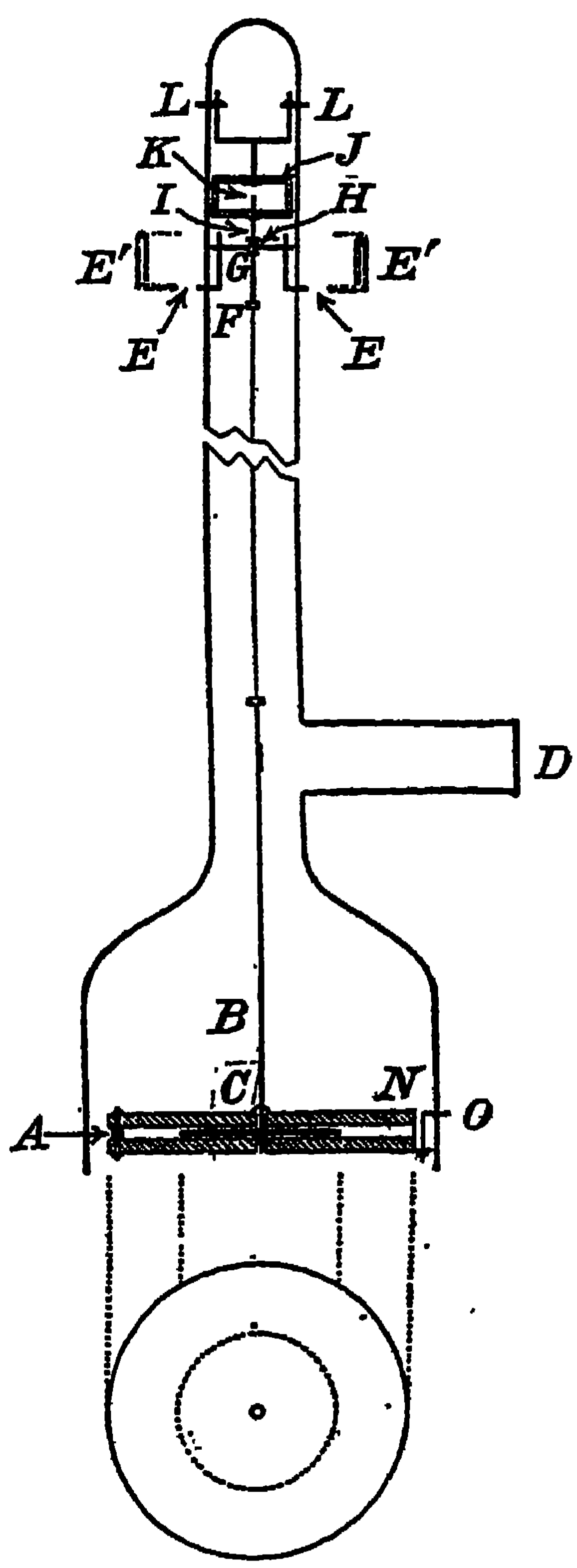


FIG. 32.—Sutherland and Hogg Decrement Gauge.

An exactly analogous case is a pendulum vibrating in a relatively less viscid medium as water and in a highly viscid medium as a thick oil. It is well known that the pendulum loses its energy of motion more quickly in the oil than in water and in water more quickly than in air, the rate of loss being dependent upon the viscosities of the various media.

Given that the velocity varies with the viscosity and this in turn with the gas pressure, it should be possible to obtain the relative value of the gas pressure by measurements of the velocity of a rotating body in the gas.

Two types of such pressure gauges are possible, namely;

(1) Decrement or dynamic gauges.

(2) Static gauges.

In the decrement type of gauge (Fig. 32), due to Sutherland and Hogg, a thin glass disc A is suspended between two horizontal plates N. The glass disc on its supporting wire B is given, by means of a soft iron armature J and an external magnet E′, a definite rotational velocity. The rate at which it loses this given velocity is measured, by means of a mirror, by observation *viâ* the window D. From such observations, since the time

of decay of oscillation is dependent upon the gas pressure, it is possible to obtain a measure of pressure to an accuracy of ·0004 mm. of mercury. Similar decrement gauges have been used by Langmuir.

The static type of gauge was suggested and produced by Langmuir and is shown in Fig. 33.

A rotating aluminium disc A is driven, at a definite speed, by means of a magnetic vane NS, set in motion at a given speed by the external magnetic coils GG. To avoid friction this armature is rotated upon jewelled points.

If a further mica disc C is suspended above the disc A, any motion imparted to A will set up a similar motion in C.

This follows, since A in its motion must set the intervening gas molecules in motion, as already stated. If the distance between A and C is sufficiently small some of the gas molecules, having acquired a certain velocity from A, will pass to C and by impact communicate their energies and direction of motion to C. The resultant energy is sufficient to cause a definite degree of partial rotation about a suspending quartz fibre F.

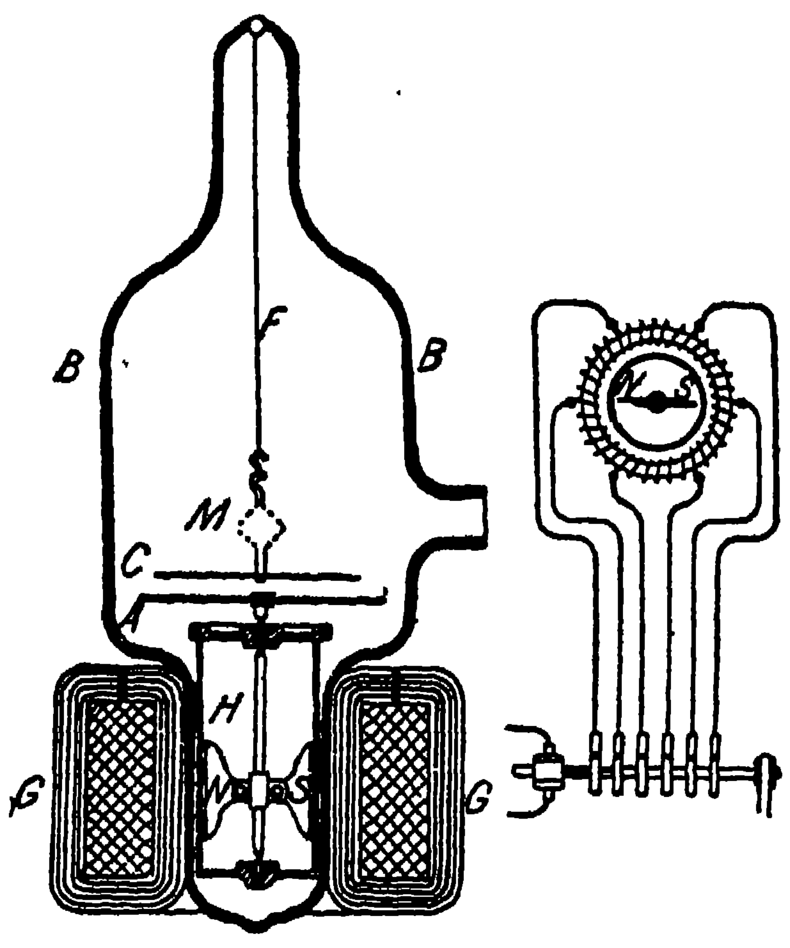


FIG. 33.—Langmuir Static Viscosity Gauge.

This degree of motion is measured by reflection from a mirror M and is dependent upon ;

(1) The speed of the plate A.

(2) The number of gas molecules between A and C, *i.e.*, the gas pressure.

Maintaining a constant speed of rotation of the plate, by means of the external rotating magnetic field, the rotation of the mirror M gives a reading, the value of which is dependent on, and is a measure of the gas pressure.

Variation of motor speed allows a variation of sensitiveness of the instrument which will give readings to the order of $10^{-4}$ bar, or $10^{-7}$ mm. of mercury.

Below this value, errors occur due to electrical eddy currents in the metallic vanes and the tendency for C to swing rather than to rotate.

Whilst the method involves rotation it is termed a static method, since the disc is maintained at a statical or constant deflection.

Of these various methods 2, 3 and 4, are absolute methods, whereas 1, 5, 6, and 7 are empirical methods needing prior calibration although, in the case of 7, it is possible to develop a mathematical theory. As already mentioned the Macleod gauge is the most widely used method, the

*Sensitiveness of Various Manometers*

| Method. | | Sensitiveness. Millimetres of Mercury. |
|---|---|---|
| 1. Deflection of Membrane | | $10^{-4}$ |
| 2. Difference of Mercury Level | | $10^{-2}$ |
| 3. Macleod Gauge | | $10^{-4}$ |
| 4. Knudsen's Radiometric Gauge | | $10^{-9}$ |
| 5. Variation of Resistance Method | | $10^{-5}$ |
| 6. Ionisation Method | | $10^{-6}$ |
| 7. Viscosity Method | (1) Decrement | $10^{-4}$ |
| | (2) Static | $10^{-7}$ |

Knudsen gauge the method of election for extreme accuracy, whereas the resistance and ionisation methods are very suitable for industrial processes, as lamp and X-ray tube exhaustion.

To calibrate such empirical gauges a system of large and small vessels are used, the smaller vessels A, B and C (Fig. 34) of say 30 c.c. capacity and the larger vessels D and E of 3 litres capacity.

This system of bulbs is evacuated to the highest possible degree, after which the vessel is shut off from the remaining vessels and a known

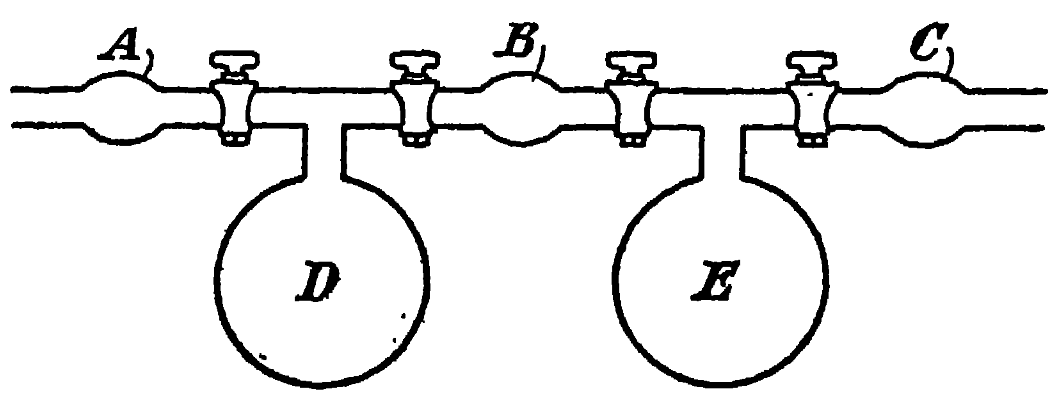



FIG. 34.

quantity of a permanent gas, at a known reasonably low pressure, is introduced into A.

This gas is then shared with D and the volumes being known the common pressure is deduced by Boyle's Law. These vessels are then put into communication with B, the common pressure being similarly deduced.

B is now separated by its stop-cocks and then shared with E and again the much-reduced pressure is calculated, the process being repeated to give any desired low pressure. Certain precautions have to be taken as regards the additional volumes of the connections and equality of pressure in the various bulbs, and the whole method is based upon the view that the original pressure is so low that it is negligible and approaches absolute vacuum, an assumption, even when the final pressure is extremely low, not justified, but sufficiently accurate for many purposes of calibration.

## PRACTICAL POINTS IN HIGH-VACUA TECHNOLOGY

*Connections.*—It is a well-known fact in hydraulics that it is useless to connect a pump with a great output per unit time to a reservoir by means of a system of narrow pipes. If this is the case the pump cannot exert its full efficiency as, owing to viscosity, there is a very large resistance at the narrow connectors of the system.

The effect is somewhat analogous to electrical resistance, since the wider the bore of the connections for a given hydraulic pressure or potential, the greater is the flow of liquid and *vice versâ*.

It can therefore for a gas be expressed in the form of an equation;

$$\frac{1}{S_2} = \frac{1}{S_1} + \frac{1}{u_1},$$

where $S_1$ = the apparent speed of the pump,
$S_2$ = the true speed of the pump,
and $u_1$ = the product of pressure and volume of gas extracted per second.

Since the value of $u_1$ represents a resistance it is useless in a high-vacua pumping system to connect a high-speed exhausting pump to the vessel to be exhausted by a small bore connection, as the speed of pumping may be reduced by as much as 35 per cent. by such connections, which should, to avoid largely the resistance effect, be of tubes of at least $\frac{1}{2}$-in. diameter.

However wide the bore of such tubes, by introducing the effect of viscosity, they must reduce the pumping speed and should therefore be kept as short as possible. The case is quite analogous to electrical measurements with a potentimeter where, to avoid potential fall in the connections, these are made by the shortest possible length of wide strip copper.

Where possible all rubber connections should be avoided in preference to glass connections, since they cannot be heated to drive off occluded gases as is the case with glass.

Rubber also evolves gaseous sulphur products, and to remove the bulk of the sulphur content such tubes should be previously boiled in 10 per cent. caustic soda solution, well washed in distilled water and dried by pumping dust-free dry air *viâ* the tubes. They should be kept as short as possible.

To join lengths of tubing this may be fused together, if glass, or sealed by suitable compound adhesives. The former method is always the best, since glass tubes can be more rapidly fused together than sealed together and then permit of the application of heat to drive off adsorbed gases, which cannot be done efficiently with seals. Also the location of leaks is much easier in a fused connection than in a sealed connection.

When seals are employed common sealing wax is often used in comparatively high pressure work. For higher vacua Klotinski's cement is used, which consists of rubber dissolved in 10 per cent. of its weight of North Caroline oil. Another cement is that of Golaz ; resin 3, beeswax 1, (1) powdered brick 4, by weight.

Narrow tap connections should be avoided, as to insert a narrow bore tap in a wide bore connection immediately removes the advantage of such wide bore. To avoid leakage troubles due to possible longitudinal striæ in the glass the ducts should be oblique. They may be greased by a mixture of vaseline 1, rubber 2, and paraffin 1, parts by weight.*

The General Electric Company have largely employed valves of the form shown in Fig. 35. The mercury normally seals the route from primary to secondary vacuum by admission of air *viâ a*, the pressure of which forces the mercury up into the right-hand bulb. When it is desired to open the route *viâ* primary and secondary vacuum *a* is closed and *b*, also communicating with the secondary vacuum, is opened and the mercury falls in the right-hand bulb and then the route between primary and secondary vacuum is open and capable of rapid resealing by merely closing *b* and opening *a*.

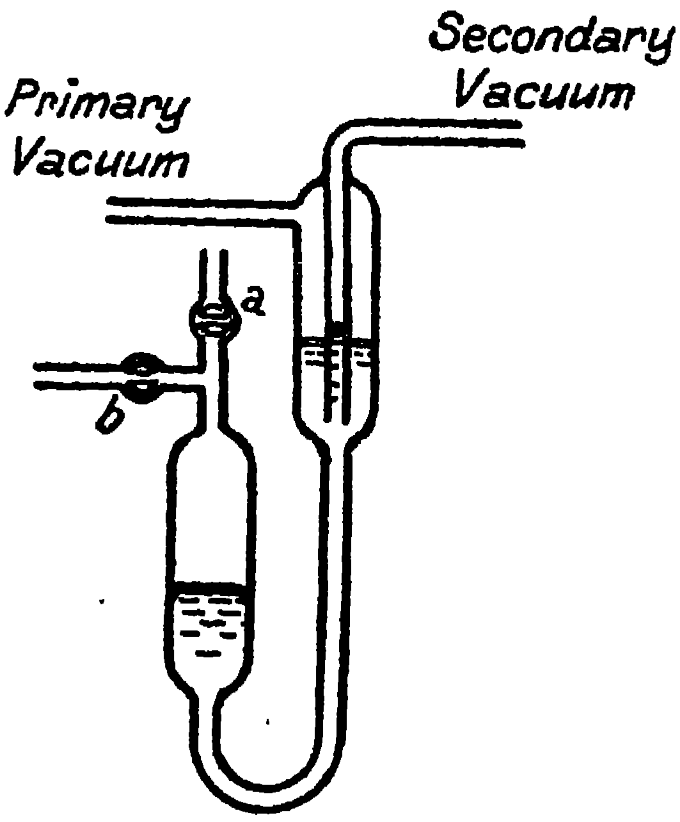



FIG. 35.

Leaks in a vacuum system are most easily sought, in the case of glass, by means of a small induction coil. One secondary terminal is connected to the internal mercury and the other, upon an insulating handle, is passed over the suspected connections.

A luminous discharge *viâ* the rarefied gas path generally occurs unless the pressure is below the ionisation value, but in the case of a definite leak a spark occurs when the insulated electrode reaches the region of leak. Failing such a testing coil, a fault may be found by immersing the tube or vessel in water and pumping air into it, similarly to the location of a pneumatic tyre puncture.

Failing the possibility of such an inconvenient immersion, a less certain method is to cover the exterior of the vessel with soap-suds and to create an internal pressure.

These methods, unlike the induction-coil exploring method, are applicable to both glass and metal tubes. Small leaks may greatly

* Schirmann (*Phys. Zeits.*, 27, p. 659, 1926) utilises metallic stop-cocks within a glass sleeve external to which is a metallic sleeve. A potential is then applied between the metal cock and metal sleeve and, owing to the Johnsen-Rahbek effect, gas is prevented from passing *viâ* the air layer between the moving surfaces. The same principle is applied to connections to prevent leakage.

reduce the speed of a high-speed pump and for this reason it is a good practice to varnish as completely as possible all pumping connections.

Where a tube, as an X-ray tube, has to be sealed off a pumping system, the thickness of the glass of the tube should not be too great, since, during heating for sealing, much gas will be evolved from the glass and reduce the vacuum. To remove the gas, inevitably given off in such an operation, the pump should be allowed to operate for a few minutes after softening the glass before this is finally pressed together.*

## ELIMINATION OF VAPOURS

In a pumping system we may have vapours due to ;

(1) Mercury, if mercury pumps are used.

(2) Oil, if oil pumps are used.

(3) Water vapour.

The first two vapours may be eliminated by inserting between the pump and vessel to be evacuated a Dewar flask cooled by carbon dioxide snow, or better, liquid air, the cold produced causing condensation of these vapours.

Water vapour may be eliminated by inserting a trap containing phosphorus pentoxide, which is well known to have a very great chemical affinity for water.

Water vapour is also eliminated by many of the bodies used to "clean-up" the vacuum (see p. 37).

The use of cold baths to remove vapours introduces variations in the flow of the residual gases *viâ* the pumping system, causing a double local subsidiary circulation of gas.

At the periphery of the duct there is a flow from the lower to the higher temperature region and at the centre from the higher to the lower temperature region, so that one of these currents tends to oppose the evacuation flow and so to reduce the pumping speed. The magnitude of each local current is dependent upon the gas pressure and at higher pressures the general direction of flow may be reversed. The explanation of such currents is to be sought upon the basis of the kinetic theory, in the case of high degrees of vacua the molecules receiving energy which, owing to their large free mean paths, causes them to pass away from the region of temperature variation and as a result colder molecules enter to take their place and so to cause a circulation of gas. When the gas pressure is high this cannot occur and gravitational effects may predominate.

* Schirmann (*Phys. Zeits.*, 27, p. 659, 1926) to reduce the gas evolved during sealing, suggests the use of a long sealing-off tube and sealing it at the point distant to the vessel. The resistance of the narrow tube towards the vessel then prevents the backward passage of gas which more easily passes to the pump, whereas with a short low resistance tube the less resistant path is towards the vessel. Such a long sealing off tube is, however, often mechanically inconvenient.

## SEALING METAL AND GLASS

It is well known that since the coefficients of expansion of glass and platinum are approximately equal, these media can be easily sealed together and such seals will withstand, without fracture, fairly high temperature variations. Since the coefficients of expansion of base metals, as copper and iron, differ considerably from that of glass, attempts to seal these metals into glass usually fail and the seals, if made, will not withstand temperature changes.

Housekeeper * of the American Western Electric Company has devoted attention to the sealing of common metals to glass, with considerable success, to enable large masses of copper to be sealed into glass for the manufacture of heavy power wireless vacuum valves.

Housekeeper's methods may be summarised by saying that the relative thicknesses of metal and glass are so proportioned to prevent fracture.

Just as we have seen (Chapter I., Vol. I.) it is necessary to proportion suitably insulation layers to withstand high electrical pressures, so is it necessary to proportion a glass-and-metal seal, in order to prevent great inequalities of expansion or contraction, resulting in the elastic stresses of the media being exceeded by variations of expansion.

Housekeeper points out that the form of the more commonly used round type of wire is such as to give greatest inequality of expansion, except as with platinum, where this is of the same degree.

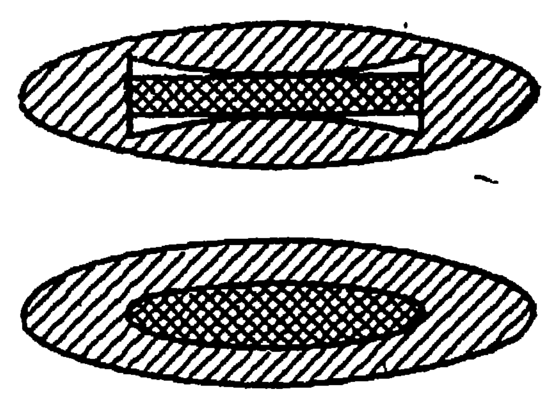


FIG. 36.

If a flat wire is sealed into glass as in Fig. 36, *a*, then observation shows that fracture results in consequence of stresses set up at the edges of the rectangle where the glass draws away on cooling from the metal edges as shown. If however the thickness of copper is graduated by use of an oval section (Fig. 36, *b*) the contraction tensions are so distributed as to avoid the elastic stress limits being exceeded and a perfect seal results, capable of withstanding extreme temperature variations.

The difficulty with base metals has hitherto resulted from the practically universal use of round metal instead of metal of suitable cross section, and Housekeeper has shown it is quite possible to form satisfactory copper-and-glass seals of very wide bore, up to about 10 cm., if care is taken to suitably proportion the seal.

Various alloys are known which have the same coefficient of expansion of glass, for example "platinor," which consists of 54 per cent. of iron (with 15 per cent. of carbon) and 46 per cent. of nickel.

* *Elect. Communications, Western Elect. Co.*, p. 15 (1922). *Jour. Amer. Inst. of Elect. Engs.*, 42, p. 954 (1923).

Philips of Holland have used with success in their metallic valves and X-ray tubes chrome iron alloys. Details of these are given in Brit. Patent 205,784. A 20 per cent. chromium and 80 per cent. iron alloy gives a metal suitable for soda glass, and the relative proportions of the metals are suitably varied for glasses of other compositions.

A similar nickel-iron alloy is suitable for lead glass and a molybdenum-tungsten alloy is suitable for Pyrex (sodium and magnesium boro-silicate) glass.

A further method of sealing glass is due to Cailletet. This consists of a multi-stage operation in which a mirror of platinum is first deposited upon the glass, by heating platinum chloride in oily suspension upon the glass. Upon this platinum mirror copper is deposited electrically, and to this copper layer of any desired thickness, tin and other metals may be easily soldered.

In all such glass-and-metal joints, in all electric discharge apparatus, there is a very great risk of fracture, not by primary irregularities of expansion, but due to variation of the electrostatic field in the neighbourhood of the glass (of good dielectric capacity) and the metal (a conductor of infinitely small dielectric capacity). Electrons and ions therefore accelerate in the region of this field and by bombardment at the potentially weak joint, cause fracture by the considerable overheating which results from such localised bombardment.

To overcome such a danger it has been the practice to either provide a metal shield or to extend the metal from the joint over the surface of the glass, and so to remove the region of the dangerous dielectric variation to a region away from the weak joint, to a region where the glass has not been weakened by the joining operation.

Philips of Holland use, in their metal X-ray tube, a still more extensive protection system, in which metallic foil is carried over the joint as above and, in addition, various labyrinth shields are provided so that no electrons are able to travel directly, with high velocities, from the high potential tube anode to the joint (see p. 69).

## LOSS OF VACUUM DUE TO OCCLUSION OF GAS FROM VESSEL WALLS

A sealed vessel which has been pumped to ·1 bar may after a few hours show a pressure of 10 bars, or above, if the vessel walls are heated.

To avoid the lowering of vacuum due to such disengagement of gas from the vessel walls it is necessary, before final sealing, to heat strongly the walls.

If the vessel after the second pumping is allowed to cool and then again heated, gas will be again evolved and the process can be nearly

indefinitely repeated, since whilst the quantity of gas evolved at each heating continually decreases, there is always some evolution of gas.

To explain this phenomenon Langmuir has suggested a theory in which the gas adsorbed by the vessel walls is supposed to be held to the walls by the weak residual chemical valencies of the atoms of the vessel wall. Combination and dissociation are continually occurring between the wall atoms and the gas, with a balance of dissociation as the vessel walls are heated.

Amongst the gases so evolved the most common are carbon dioxide, oxygen and nitrogen and also water vapour.

Since final and complete evolution of such gases can never be obtained, it is necessary to heat the walls of evacuated vessels, as thermionic valves and X-ray tubes, to temperatures much above those at which such apparatus will operate in practice, in order to minimise the loss of vacuum due to such gas disengagement, unless the apparatus is greatly overloaded, the disengagement being otherwise negligible.

To carry such heating to an extreme degree, *i.e.*, to the point where the glass wall of the vessel begins to soften, it is necessary to enclose the tube in an electrically heated vacuum furnace, where the external gas pressure can be reduced to equal approximately the internal pressure and there is no risk of collapse of the softened tube walls, by reason of a high external pressure.

The nature of the glass influences the degree to which such heating can be allowed, for example, whereas soda glass will only allow the application of a temperature of 400° C., and lead glass still less, namely, 360° C., Pyrex glass will permit a temperature of 500° C.

Metals in such heating processes allow still higher temperatures, but adsorbed gases are more difficult to disengage completely. Whilst silica allows much higher temperatures than glass, this advantage is offset by the difficulty in working silica.

The final result as regards such disengagement of gases is (similarly to the activation of charcoal for adsorption purposes) dependent upon the conditions of heating. The best results are not obtained by the most intense heat for the longest period, but by repeated heatings of less degree.

Gas is also given off from the metal parts of vacua tubes as X-ray tubes, and this becomes of importance where, in the electron X-ray tube, the anode may, during operation, reach a temperature of incandescence. Platinum, by its well-known adsorption of gas, with evolution of gas on heating, shows considerable variation of pressure due to this cause and it is one of the advantages of tungsten over platinum for X-ray tube targets that tungsten exhibits much less powers of such adsorption, as well as non-heated tungsten parts tending to absorb such gas by oxide formation.

In the early stages of exhaustion however tungsten may evolve

considerable quantities of hydrogen, the origin of which is the decomposition of water vapour in the gas to form tungstic oxide with evolution of the hydrogen of the water.

At high temperatures such tungstic oxide breaks up with evolution of oxygen. Heating such a filament in a vacuum therefore tends to "clean-up" residual water vapour and the gases separately evolved, *i.e.*, oxygen and hydrogen can then be easily pumped off.

Before sealing off, all metal parts of high-vacua tubes must be heated to a much greater degree than will occur in practice, to cause gas evolution. This is done in a vacuum furnace, and methods have been evolved, particularly by the American G.E.C., of casting and forging metal parts such as electrodes *in vacuo*, to evade excessive gas adsorption.

After sealing into the vacuum tubes and before final sealing off of the bulb, the metal parts are further heated by the passage of heavy currents at voltages much above the normal operating voltages, the temperature rise, due to electronic bombardment, aiding the further evolution of gases.

Since in such a process, X-radiation is evolved, vacuum ovens must be protected by a suitable thickness of X-ray protective material, built into its walls to avoid danger to the operators.

Such vacuum ovens usually consist of a large chamber upon supports and in the floor of which a tube (or tubes) is inserted upon which the X-ray tube, held by suitable clamps, is sealed. This tube so makes connection to the exhaustion plant, commonly placed below the raised oven and between its supports (Fig. 37). Terminals are provided in the sides to which the high-tension energy for the tube excitation is led. In order to prevent any danger from such high tension when the oven is opened and the tension is inadvertently allowed to be still existent, suitable low-tension contacts of the operating transformer are inserted in the oven sliding front, so that current can only pass to the transformer when the oven front is closed.

The heavily protected oven front, with a suitably thick lead-glass window, is balanced with suitable counterpoise weights in order to allow easy movement.

If a rough vacuum, external to the tube, to allow a high degree of external vacuum to be applied to the tube whilst this is being heated, is to be utilized, then an exhaust for the oven must be provided and the oven door be rendered suitably air-tight by clamps, or other means. Heating within the oven is provided by electrical means.

The protection is usually lead sheet, with overlapping edges, upon a badly conducting internal plaster, with an internal metal air-tight casing. Heavy static shocks can be obtained, by contact with the external metal protection, when the high-tension energy is applied, due to the condenser action of the internal and external metallic layers. To avoid such shocks the use of non-metallic protective barium plaster (*q.v.*, Chapter VIII.,

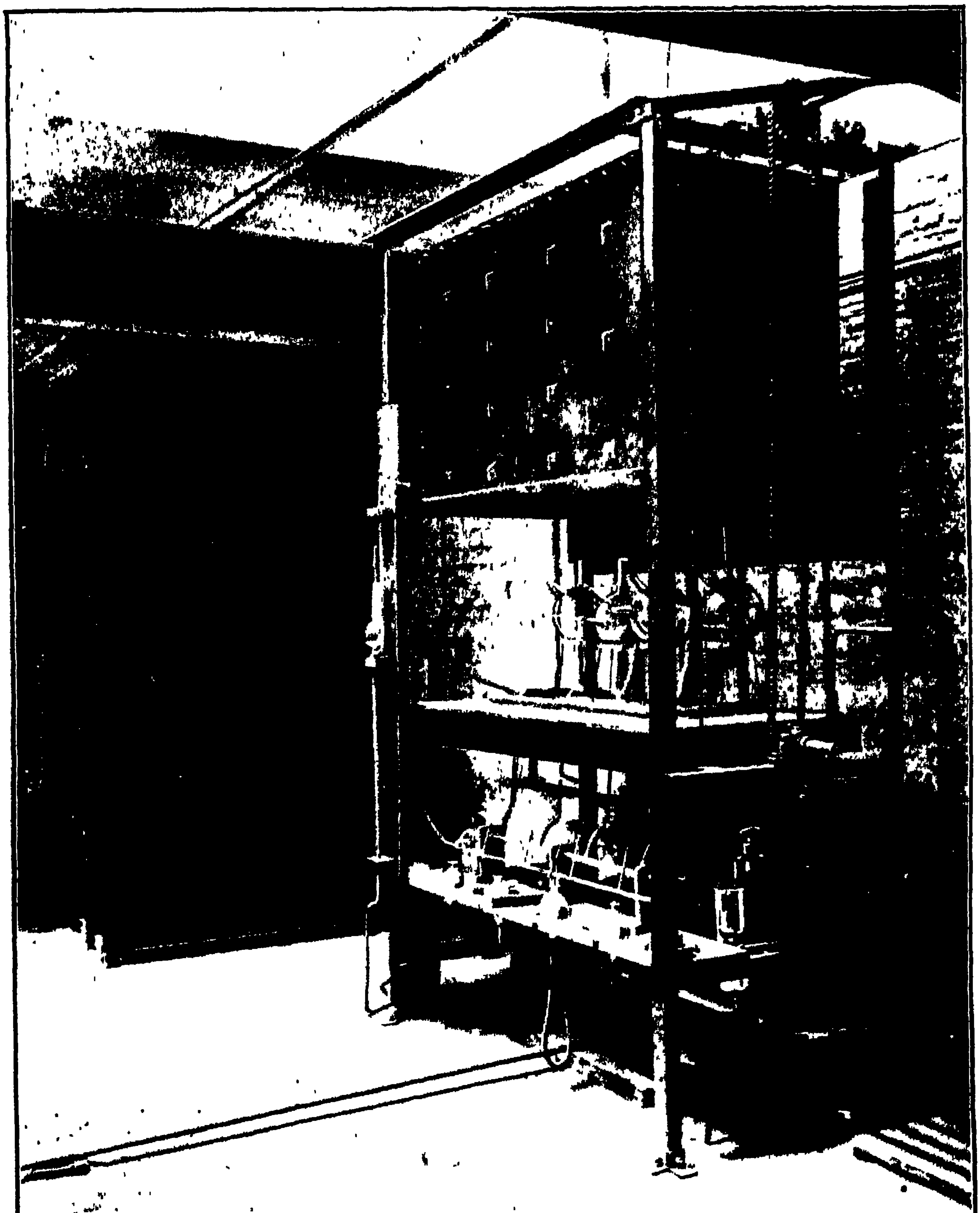


FIG. 37.—Protected X-ray Tube Oven.

[To face p. 56.

[illegible]

Vol. II.), would be preferable to sheet lead, but has not been utilised, as far as the author's knowledge permits.

## EXERCISES ON CHAPTER I

*Question* 1 *is based upon an analogous question set in the D.M.R.E. Examinations of Cambridge.*

(1) A glass tube is provided with two electrodes and is evacuated whilst connected to a running induction coil. Describe the various visual effects of the discharge as the tube is exhausted. Describe or sketch a pumping system to evacuate X-ray tubes.

(2) Describe the action of the mercury vapour vacuum pump.

(3) Describe the rotary oil vacuum pump.

(4) Discuss the various causes which are responsible for the increase of vacuum of a gas X-ray tube after long use.

(5) How is the pressure of a low vacuum measured and on what physical principles is such a gauge based.

(6) What are the disadvantages of the Macleod gauge ?

(7) Give a diagram of a metal mercury vapour pump.

(8) Give reasons to show the Langmuir condensation pump is a special case of the Gaede mercury vapour diffusion pump.

(9) Why is a fore vacuum necessary in a mercury vapour pump without a slit aperture ?

(10) Compare the rotary oil and mercury vapour pumps in the degree of vacuum obtainable.

(11) Classify the methods of obtaining high vacua and define the units in which such vacua are measured.

(12) How would you eliminate vapours from a highly evacuated space ?

# CHAPTER II

## THE X-RAY TUBE

### GENERAL CONSIDERATIONS. THE IONIC OR GAS TUBE

AS a basis of study of X-radiation tubes these may be classified in various manners. The most rational classification is ;

(*a*) *Gas or ionic tubes* depending upon gaseous ionisation for the production of electrons constituting the current.

(*b*) *Electron tubes* dependent upon the production of electrons by thermionic emission from heated filaments. A sub-group of this class are the auto-electronic tubes of Lilienfeld, not directly dependent upon thermionic phenomena.

Either ionic or electronic tubes may have an envelope of glass or metal, and we could therefore adopt an alternative classification :

(*a*) Glass X-ray tubes (including silica tubes).

(*b*) Metal tubes.

For our purposes a combination of these two classifications will be more convenient, *i.e.* ;—

(*a*) gas or ionic tubes,

(*b*) electron tubes,

(*c*) metal tubes, either of types *a* or *b*.

This classification is not however a strict one and a strong line of demarcation cannot be drawn, since it will be convenient to refer to some details of electron tubes when referring to gas tubes.

### INTRODUCTORY AND HISTORICAL

The original X-ray tube of Röntgen* was one of the innumerable forms of gas discharge tubes which, developed by the early experiments of Plückner, Geissler and others about 1860, were, during the end of the nineteenth century, much used in quasi-scientific experiments for the production of beautiful coloured effects of gas discharges.

The later and more rigorous scientific study of these effects, paving the way to the discovery of the electron, is very largely due to the English physicist, Sir W. Crookes.

The form of Röntgen's tube is shown in Fig. 38, and whilst such a tube

* Röntgen's discovery was announced in the *Bericht der phy. med. Ges.* of Würzburg University, a first communication appearing in December, 1895, and a second communication in March, 1896. This journal is difficult to obtain in England, but an English translation appeared in *The American Journal of Röntgenology*, 10, p. 320, 1923, and this was reprinted in *The Journal of the Röntgen Society*, 19, p. 112, 1923.

is very inefficient as a practical X-ray tube it was the forerunner of all X-ray tubes.

Such a tube suffered from the defect that the electrons from the cathode C were not focussed upon the anode A, and the radiation from the glass wall gave, in consequence, only a very blurred photographic image. The life of the tube was also very short, chiefly owing to the lack of robustness of the anode and to rapid variation of the vacuum.

The lack of focus of the electron beam upon the anode is the chief factor responsible for the poorness of the early X-ray plates often shown, somewhat unfairly, contrasted with plates taken by the later focussed tube.

Other than the improvement due to focussing one may say the modern ionic X-ray tube differs very little from this original tube, except as regards the size and increased weight of the electrodes, to allow of the passage of greater energy.

The lag of development of the X-ray tube is surprising. Such develop-

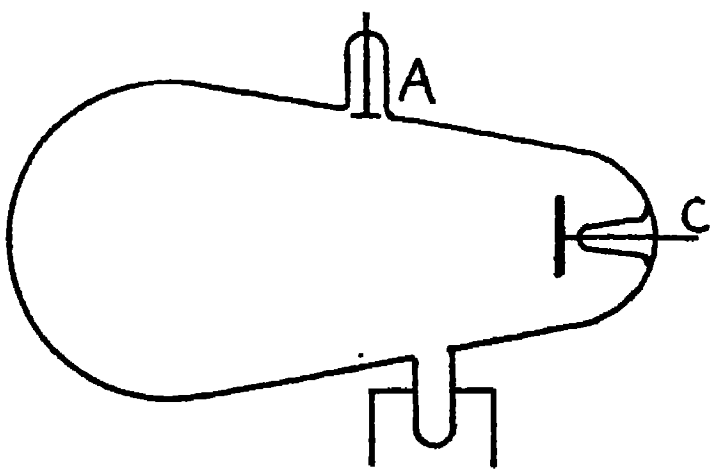



FIG. 38.—Röntgen's X-ray Tube.

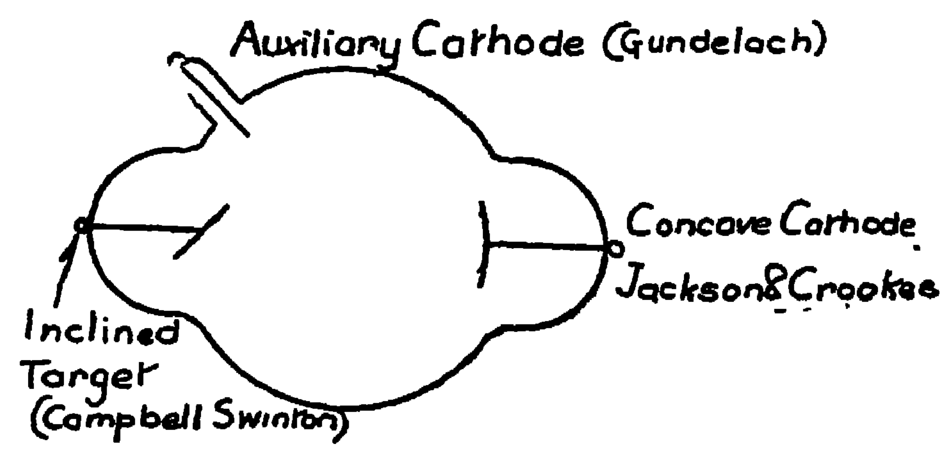



FIG. 39.—Later Modifications to Röntgen's Tube.

ment lags very far behind our means of producing the necessary high-tension energy to excite such tubes.

No difficulties now exist for the supply of energy of any desired power at voltages sufficient to operate directly X-ray tubes.

On the contrary it is becoming more and more common abroad, particularly in the U.S.A. and Germany to distribute electrical energy at voltages ranging from 100 kv. to 200 kv. Such voltages are more than necessary to operate directly X-ray tubes for diagnostic purposes and, the higher values, for direct therapeutic X-ray tube excitation.

That the X-ray tube so lags behind is doubtless due to the fact that its manufacture has hardly left the laboratory stage and is only just entering into the engineering stage.

Exactly the same situation arose in the early history of the thermionic valve, now so extensively used in radio transmission. Such valves were in the early days of negligible output, very erratic in their behaviour and very expensive. When the demand for valves of greater output and stability arose, their manufacture passed from the physical laboratory of the instrument maker, to the engineering lamp works. As a result, there now exist thermionic valves of silica or of metal capable of handling

amounts of energy up to 100 kw. and more and voltages up to 100–250 kv.

It is to be hoped that more attention will be devoted to X-ray tube production and particularly to cheapening these necessary medical apparatuses, the prices of which are often out of all proportion to their cost of production.

The two most noticable modifications of Röntgen's original X-ray tube (Fig. 39) are usually stated * to be ;—

(1) The substitution in 1896, by Campbell Swinton (and also by E. Böhm†) of an inclined anode, so giving the X-radiation a more specific direction.

(2) The introduction in the same year by Jackson, of a concave cathode of the type used more early by Crookes in his classical discharge experiments to show the heating effects of cathode rays. Such a cathode allows the electron beam to be more efficiently concentrated upon the target (anode).

A further modification, dating from about the same period, was the introduction of an auxiliary anode by Gundelach, chiefly for convenience of production, but also of great assistance in rendering the tube more suitable for use with the then universal induction coil. Nowadays, with the more common use of transformer excitation, this auxiliary anode tends to be omitted.

Other than the above modifications, the only improvements since 1896, have been of secondary rather than fundamental importance, such as methods of cooling the heated target to allow the passage of greater values of energy and the introduction of innumerable methods of modifying the degree of vacuum in ionic tubes.

Whilst the use of metal for the tube container appears to be regarded as a modern improvement it should be remembered that within a year of Röntgen's discovery itself, *i.e.*, 1896, B. Davis‡ successfully constructed a metal X-ray tube in which the more modern use of electrode shields was also introduced.

Similarly in the case of electron tubes, H. C. Gover and W. C. Cooke§ foreshadowed the modern filament tube by introducing a filament for purposes of modifying the vacuum. This must also have served to produce thermionic electrons as well as merely giving rise to the emission of occluded gas, and definite thermionic emission must have occurred

* The author has followed custom in attributing these modifications to Campbell Swinton and Jackson, but it is very likely they were due to Röntgen, since, in his second paper of March 9th, 1896, he states: "I have used for some weeks with good results a discharge apparatus with an hemispherical aluminium cathode and an anode of sheet platinum arranged at 45° to the axis of the cathode hemisphere and set at its centre of curvature."

† Brit. Patent 22,794/1896. This patent also shows a concave cathode and an auxiliary electrode.

‡ B. Davis, *Nature*, 54, p. 281, July 23rd, 1896.

§ Brit. Patent 13,109/1897.

in the similar heated platinum filament used by Bonetti in 1898.* Furstenau † showed, in 1912, with such a filament the current *viâ* the tube was dependent upon the filament temperature rather than the degree of evacuation.

Two years before (1910) Lilienfeld ‡ had been experimenting with

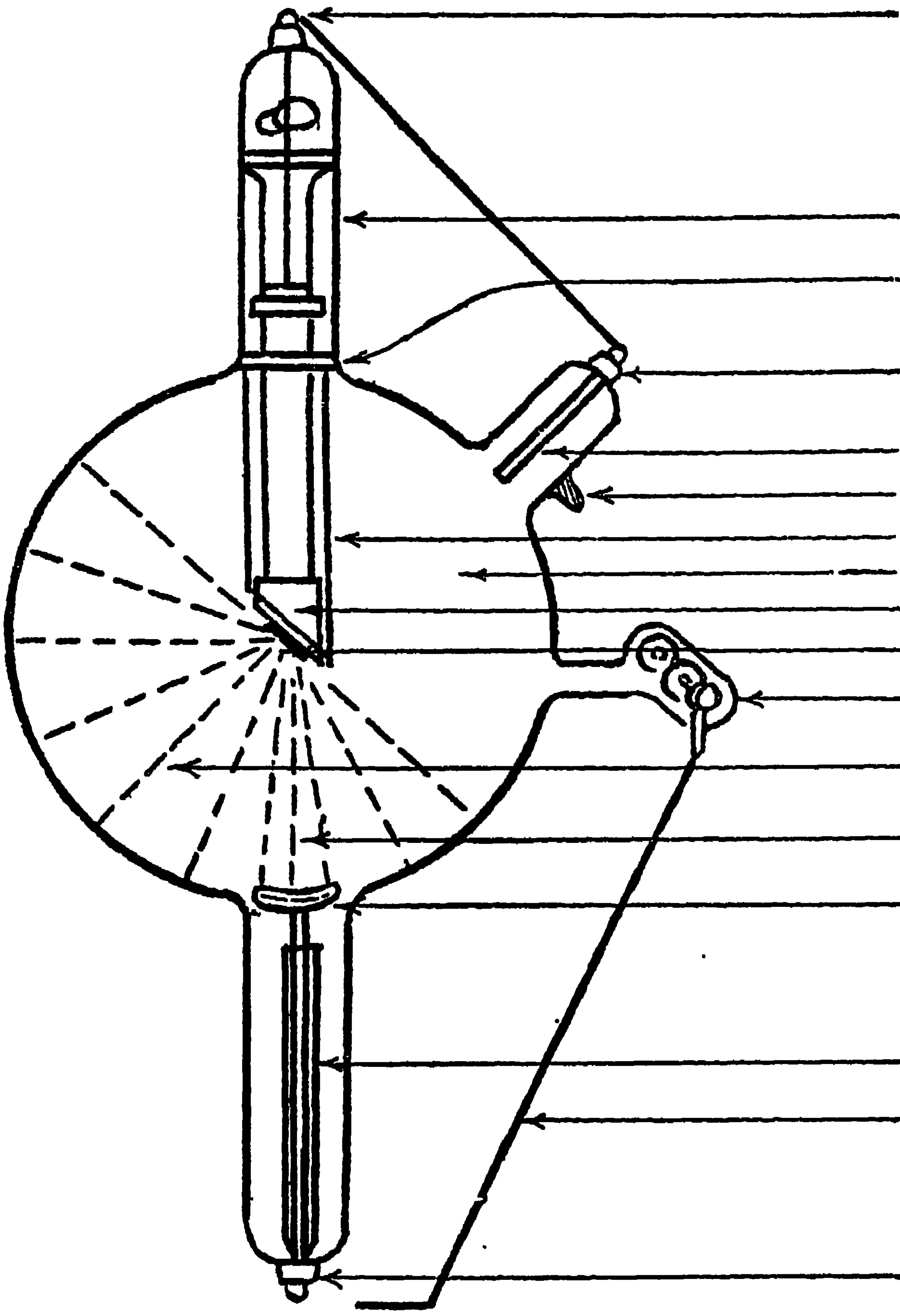



FIG. 40.—X-Ray Tube Terminology.

highly evacuated tubes, in which thermionic electrons were provided by a heated platinum Wehnelt cathode.

In the hands of Langmuir and Coolidge, to whom is due the technical production of gas-free metal for the electrodes, such tubes have been produced, to a very high degree of commercial reliability, by the General Electric Company of America, as well as by Siemens and Halske of

* *Comptes Rendus*, 126, p. 1892/1898.
† German Patent 271,306/1912.
‡ *Ann. der Phys.*, 32, p. 673 (1910).

Germany, who simultaneously developed the Furstenau tube, and by Müller.

Whilst such metal and electron tubes are now becoming common it should be appreciated they are revivals of older discoveries rather than entirely new discoveries, as commonly considered.

To deal in detail with the nature and use of the various component parts of an ionic X-ray tube, which is essentially an apparatus in which electrons are produced, either by shock ionisation or by thermionic means, and hurled, at terrific speeds, at a metal anode, by means of the applied potential, we shall find it convenient to make the following sections, in accordance with the usual nomenclature of such tubes shown in Fig. 40 ;—

(1) The envelope.
(2) The gaseous atmosphere.
(3) The control of the degree of vacuum.
(4) The cathode.
(5) The anticathode.
(6) Methods of cooling the anticathode.
(7) The anode.
(8) Practical tube operation.

## THE ENVELOPE

The phenomenon which occurs upon the glass or other envelope of an X-ray tube is by no means simple, and other effects than the pure separation of the vacuous space occurs. Indeed X-rays can be produced within an envelope of which the electrodes are entirely external, so showing the glass actually takes part in the generation of X-radiation.

The requirements of an X-ray tube envelope are ;—

(1) That it allows the production and maintenance of a high degree of vacuum, to allow the molecules of the gas within it to acquire a considerable "free mean path," *i.e.*, to travel a comparatively great distance before impact with another molecule results. This requirement necessitates the envelope being entirely impervious to gases.

(2) It must be a good dielectric to allow a very considerable potential difference to be applied to the metal electrodes with only negligible electrical leakage, chiefly over the envelope surface.

(3) It must be capable of being heated without entire loss of rigidity to allow, during exhaustion, occluded gases to be driven off from the surface.

(4) It must not enter into chemical combination with the residual gases within, so modifying the degree of vacuum.

Excluding metal envelopes which are, in view of condition (2), always only partially metal, the only two common substances fulfilling these requirements are glass and silica.

Silica may be briefly mentioned since it has been often used, notably by Dauvillier, to construct X-ray tubes and vacuum pumps. It possesses the following advantages ;—

(1) It will withstand a very high degree of heat (about 1,500° C., as compared to about 350° C. of soda glass) and therefore allows efficient removal of occluded gas during manufacture, particularly for electron tubes.

(2) Should local heating occur it will withstand very abrupt temperature variations without fracture, unlike glass, very liable to fracture if local overheating results. By virtue of this property it can be directly water cooled.

(3) It has excellent dielectric properties.

As disadvantages of the use of silica, as compared to glass, we have ;—

(1) It cannot be so easily worked, an oxy-hydrogen flame being needed during construction, with attendant difficulties of manipulation.

(2) For the short X-ray wavelengths, particularly those approaching the ultra-violet region (most objectionable from the point of view of X-ray burns) silica allows more easy passage of this soft radiation than glass. It is for this reason silica is used in ultra-violet light mercury arc apparatus. The use of silica for X-ray tubes intended for superficial skin X-ray treatment might however be very valuable, but as far as the writer is aware, experiments have not been conducted in this direction.

(3) Silica offers great technical difficulties, during the sealing in of the electrodes, owing to the great difference of the coefficients of expansion.

Of the glasses used in X-ray tubes we have to distinguish ;—(1) Soda glass. (2) Lead glass. (3) Lithium glass. (4) Pyrex glass.

*Soda glass* is essentially a double sodium and calcium silicate and the common glass of commerce. To it is added in course of manufacture manganese dioxide to produce a good colour and remove the green colour due to iron salts. It is to these salts the violet coloration of old X-ray tubes is due, owing to electrolytic action producing chemical change resulting in the formation of permanganates.

Glass for X-ray bulbs is usually procured in the form of round-bottom flasks with long necks and into these flasks the other two necks are sealed with the blow pipe. Most of the English blown bulbs are made from flasks obtained from Holland.

*Lead glass* is by no means specially produced for X-ray purposes, but has been long known as common flint glass. Of recent years special lead glasses have been produced for X-ray purposes, and Coolidge has successfully produced glass, the lead equivalent of which is no less than 25 to 50 per cent. of its thickness, so that a glass of 8 mm. thickness, *i.e.*, about $\frac{1}{3}$ in., is sufficient to give the protection usually considered as necessary for diagnostic X-ray work up to 100 kv. It is even stated glass having only 1·4 times the thickness of pure lead has been produced

by Meikle of the G.E.C. of America,* but this appears to be an experimental glass only.

Glass with such a heavy lead content cannot be blown and has to be moulded, which is not altogether a disadvantage, since this allows very gradual cooling, so that on cooling the glass is not so brittle. Lead glass rapidly attacks the pots in which it is cast and the fumes are very injurious to the workers.

It is only of recent years that thick sheets of lead glass of 1 in. or more in thickness and free from green coloration or bubbles has been produced. This is remarkable when one considers that normal flint glass is stated to contain 34 per cent. of lead oxide. Still more remarkable are the prices current for such glass, when used for X-ray purposes, if it is recollected that normal flint glass should offer very valuable protective qualities against X-radiation.

The object of using lead glass in X-ray bulbs is to cut off all undesired radiation at the source. To emit useful radiation, windows of sodium, or better, lithium glass, are fused into the lead-glass bulb. This method appears to have been first introduced into England by A. C. Cossor and H. S. Hohne.† Fig. 41 shows a Coolidge tube of this type with a soda-glass window. The difficulty in their manufacture is the jointing of the soda window, and for this reason it is more common to employ a tube of normal glass with lead-glass shields (Fig. 42).

*Lithium-glass* X-ray bulbs were introduced by Lindemann,‡ who gives as a suitable composition ;—

| | |
|---|---|
| $Li_2.B_4.O_7$. . . . . . | 83·5 per cent. |
| $B_2.O_3$. . . . . . . | 14·0 ,, |
| Gl.O. . . . . . . | 2·5 ,, |

This glass is very translucent to X-radiation, blows easily and can be easily fused to soda glass. It suffers from the defect that it is hygroscopic and, to overcome this, an external coat of varnish may be applied. Unlike soda glass it is not rendered fluorescent by ionic bombardment.

*Pyrex glass* is a magnesium boro-silicate and its chief value is that it allows the use of a much higher temperature without fusion, to drive off the surface layer of gas during exhaustion. The fusing point is about 500° C., as compared to about 350° C. for common glass, and it is roughly equally translucent to X-radiation.

*Distribution of Charge upon the Envelope.*—It is an elementary experiment of electrostatics to show that a glass rod rubbed by various materials may be either positively or negatively charged.

It is therefore equally to be expected that the glass wall of an X-ray tube subjected to bombardment by ions or electrons would be charged

* *Gen. Elect. Rev.*, p. 56–60, 1918.
† Brit. Patent 5,611/1902.
‡ French Patent 389,205/1908. Brit. Patent 8,704/1907.

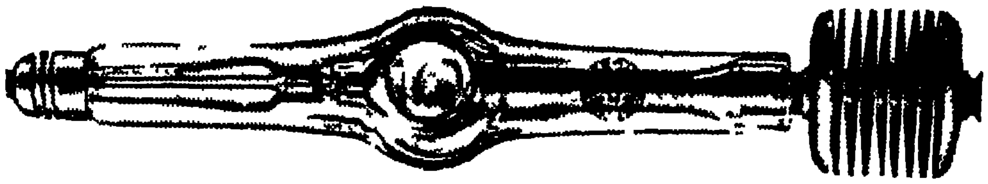


FIG. 41.—Lead-glass Coolidge Tube.

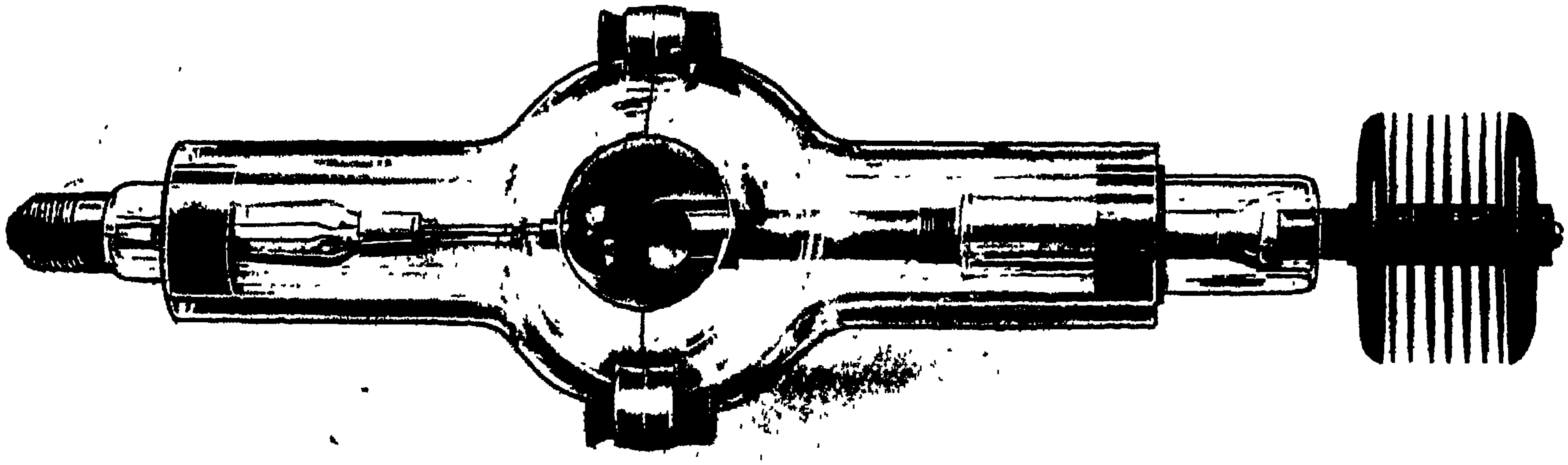


FIG. 42.—Coolidge Tube with Lead-glass Shields.

[To face p. 64.

electrically. The distribution of charge varies however in the ionic and the electron tube.

In the gas tube the current is constituted by the passage of electrons derived partly from the gas and partly from the tube walls. Since the electrons are removed by being passed from atom to atom of the metallic circuit, it is to be expected that within the gas and upon the walls of the tube there will remain the positive charges, or ions, of the atoms from which these electrons are derived. A number of these will constitute the charge upon the wall of the glass. If the X-ray tube is covered by a mixture of sulphur and powdered red lead, the sulphur will adhere to those parts having a positive charge and the red lead to those parts having a negative charge. The distribution of charge will for an ionic tube be found to be approximately as Fig. 43A.

As one would expect, since the electrons are largely produced by ionic bombardment of the walls in the ionic tube, the glass is largely charged positively and only a small region surrounding the cathode sleeve has a

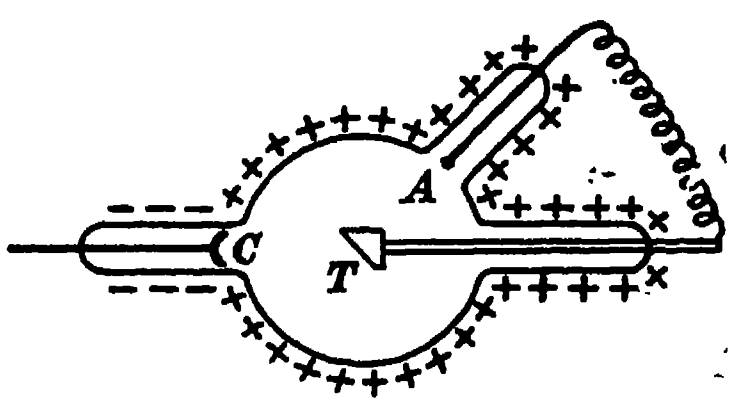



FIG. 43A.—Distribution of Charge upon a Gas Tube.

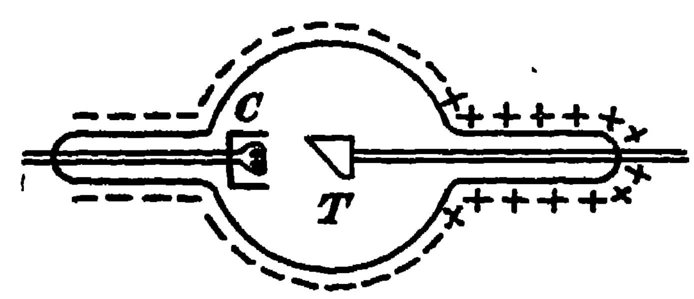



FIG. 43B.—Distribution of Charge upon an Electron Tube.

negative charge. It is in this region of separation that the greatest stress is thrown upon the glass since the positive and negative charges tend to neutralise each other, so constituting an electrical current. Such a current tends to heat the glass and increases considerably as the temperature of the glass rises until, owing to inequalities of expansion, the glass ruptures.

The well-known fluorescence of an X-ray tube is possibly due to this ionic bombardment* and is absent in electron tubes as these ions are no longer present. The colour of the fluorescence is dependent upon the nature of the glass, being yellow, blue, or green, for soda glass, blue for lead and quartz glass and absent in lithium glass. Upon modern views these colour variations are due to different frequencies of vibration of the electrons of the atoms of the glass wall, according to the particular elementary atoms of the glass, which are set in vibration by the ionic impacts. The actual demarcation of the positive and negative charges of the ionic tube is dependent upon external factors, affecting the potential

* This is the view of Dauvillier, but others, and particularly Daumann, hold that the fluorescence is produced by electronic bombardment, and the *rôle* of the ions is to neutralise the negative charge of the walls.

fall, for example, it varies as to whether the tube is immersed in oil, or is enclosed in a metal shield.

This potential source of weakness is aggravated if, at this region, the seal of the cathode sleeve and bulb is made in the X-ray tube, as such seals are always a source of mechanical weakness. Even, as should be the case, when the cathode is inserted in the neck of the round glass bulb forming the original bulb, this region is potentially weak. For this reason it is common to affix to the cathode (Fig. 44A) a shield in the form of a ring. The action of this ring is that, being positively charged as is the anticathode, it tends to repulse positive charges and, as a consequence, since the projection of this ring from the tube target falls upon the cathode neck (Fig. 44B) ions are prevented in following a direct course to this weakened region of the glass, which is so shielded from ionic bombardment.

It is often stated the action of this ring is to increase the focus, but such an action is secondary to the protective action. It is true that this ring at the same time deflects ions so that they are either thrown very wide of the cathode or towards the centre of the cathode where the focussing effect is greatest. The ring may however obscure the sharp focus of the tube by itself becoming a source of X-radiation when bombarded by electrons from the cathode. By emitting positive ions it also tends to increase the pulverisation or sputtering of the cathode (*q.v.*).

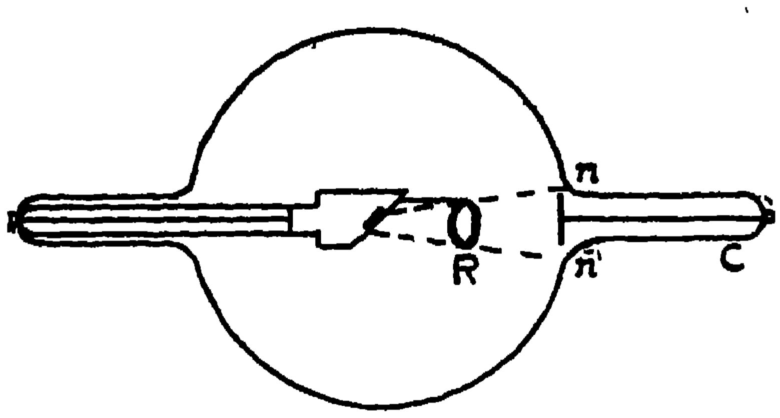


FIG. 44B.—Action of Shield Ring.

The general effect of such a shield is to render a tube more "hard" as it decreases the number of ions passing to the cathode and, as a consequence, the emission of electrons from the cathode due to this ionic bombardment, the degree of which determines the value of current. Whilst the current so decreases, the quality of the current is more valuable for the particular purpose and the heating of the target is decreased by the absence of heat produced during the excitation of unuseful radiation.

In higher voltage tubes such a method of protection is not so readily available, and to diminish the electrostatic stress over the cathode neck the cathode sleeve is made very long (Fig. 45), so that the fall from highest negative potential *viâ* zero to positive potential is more gradual, and any resulting currents and the resulting heat is more evenly distributed over the glass surface.

A similar effect and more convenient method since it is less cumbersome is to make a "re-entrant" cathode sleeve, so giving a greater length of glass. This is adopted in the glass portion of the Philips metal tube (Fig. 48).

The distribution of charge upon the electron tube is as shown in Fig. 43B and is practically the reverse to that upon the ionic tube.

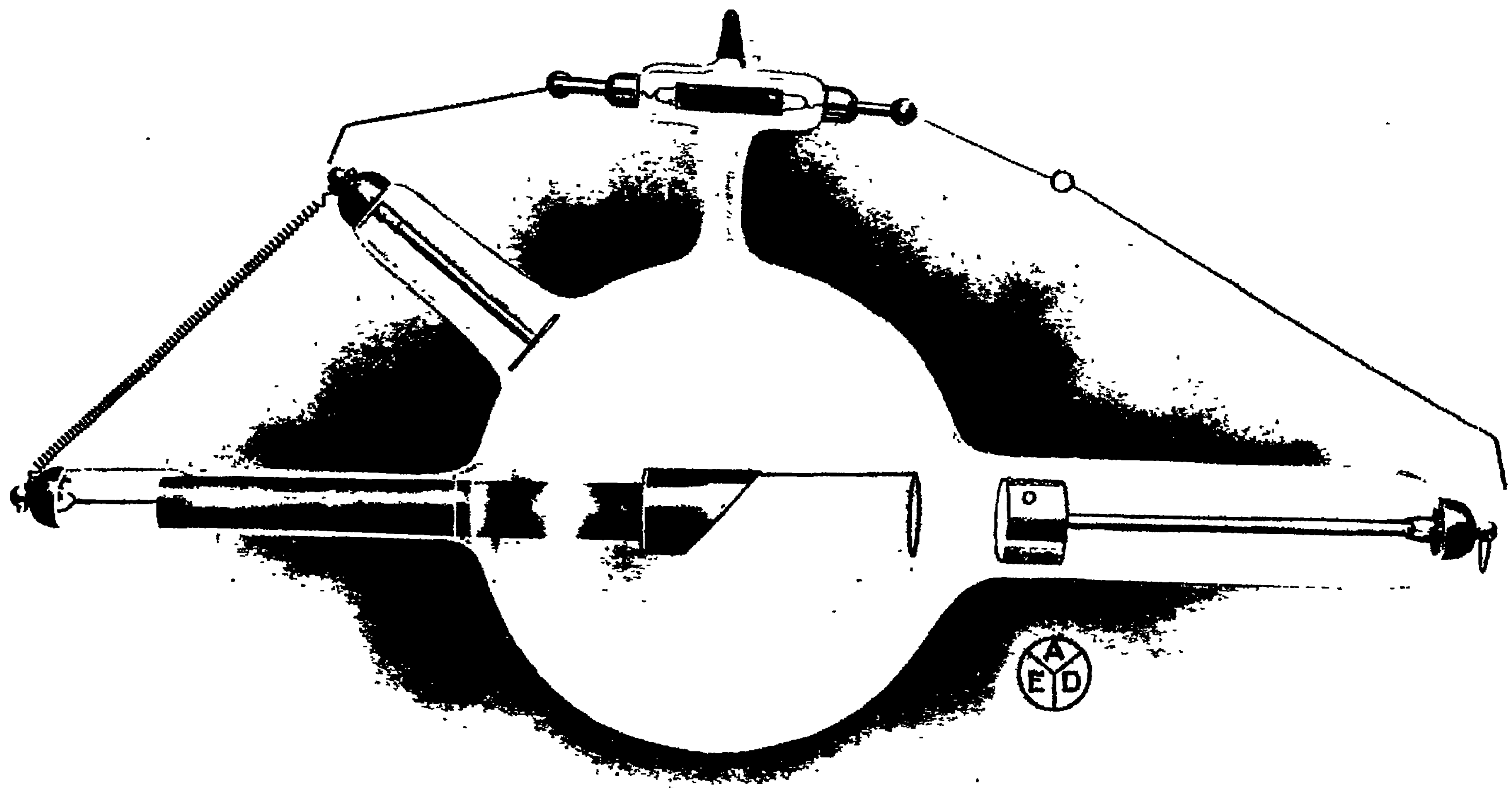



FIG. 44A.—Tube with Shield Ring (A. E. Dean).

[To face p. 66

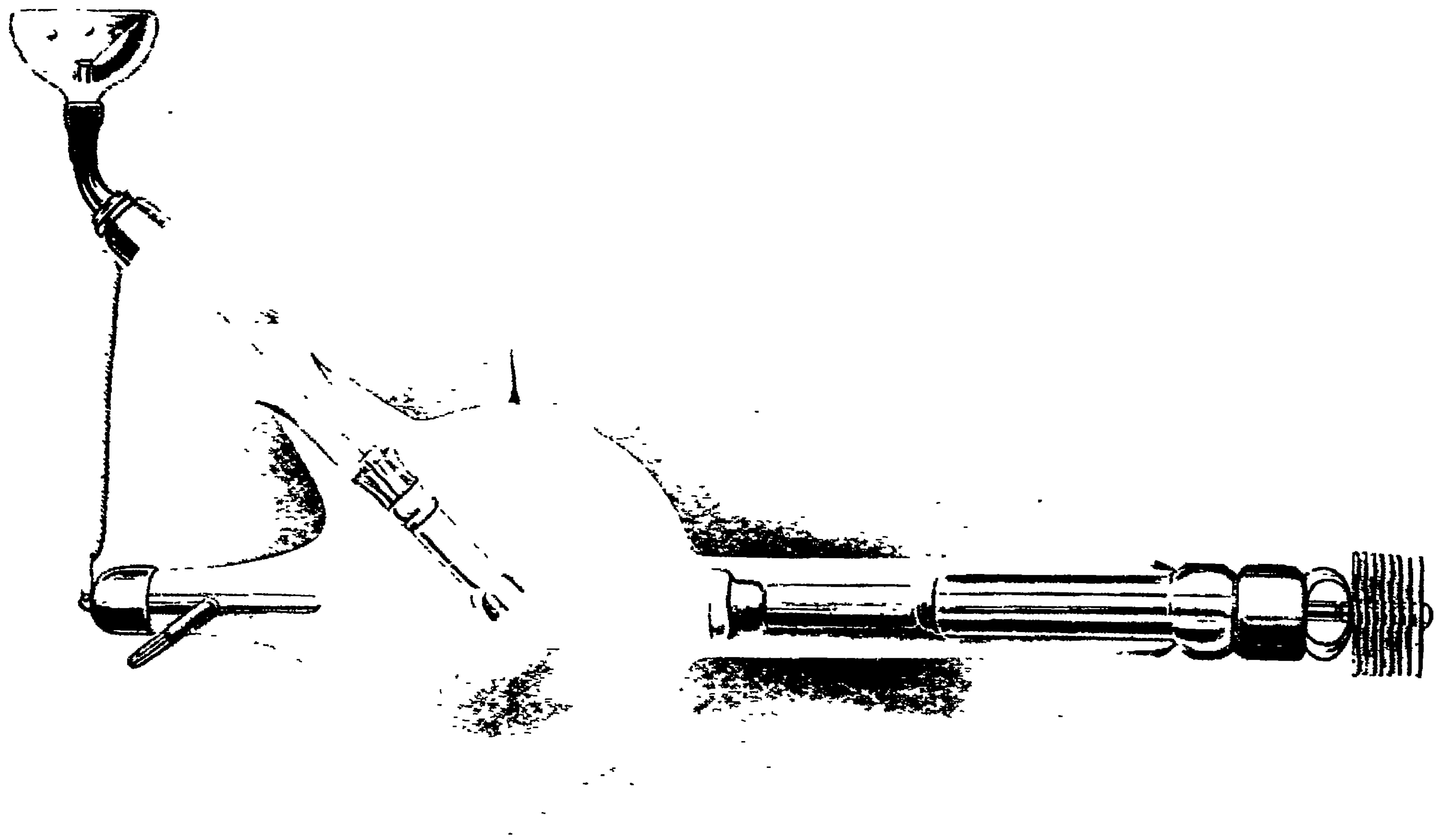


FIG. 45.—Tube with Long Cathode Sleeve to Distribute Glass Potential (Messrs. Müller).

Since ions are not existent, the only charges which can reach the envelope are the negative electrons. In consequence the envelope is strongly negatively charged, with the exception of the anode sleeve.

No important fluorescent appearance results. Whilst glass can be made to fluoresce by electron bombardment it is probable that the envelope acquires such a strong negative charge that any electrons tending to pass to the wall are repulsed owing to the similarity of charge. The "space charge," *i.e.*, the repulsive effect of the electrons in any given volume of the interior of the bulb, also aids to prevent the electronic bombardment of the walls of the tube.

Not only does this occur but the electrons are so repulsed that they follow curved orbits and return to the anode of the tube, from which they give rise to actual X-radiation. Such radiation increases the heat generation and would give rise to loss of focus were it not the rays are often so soft that they are absorbed by the envelope.

With the electron tube the envelope acquires a final but constant negative charge under the given conditions. With the ionic tube this is not the case and a constant variation of charge occurs.

In the ionic tube electrons result for the transmission of energy by actual bombardment of the wall by ions (Dauvillier).* If therefore the envelope acquires such a high charge that further ions approaching the tube wall are repulsed, then the supply of electrons for current and radiation falls off, and the charge of the envelope likewise falls, so allowing further ions to be driven to the wall. Hence the discharge of an ionic, as compared to an electronic tube, is a fluctuating and not a steady discharge and, for some purposes, such as X-ray cinematographic work, the electron tube is doubtless more efficient.

It should be mentioned that it is common for a slight fluorescent effect to occur in the region of the anode neck of electron tubes. Apparently any residual gas in the bulb congregates in this region and, due to the sudden variation of potential in this region, the ions acquire velocities which, on impact with the glass, give rise to ionisation fluorescence.

To prevent the envelope from attaining greatly different potentials over a small surface of glass it has been proposed to introduce, as in engineering practice, for example, high-tension cables (see Vol. I.), layers of conducting material to equalise such stresses.

The first attempt to do this appears to be due to W. A. Winter.† A conductive coat (Fig. 46), capable of being discharged *via* resistance of some kind is arranged in various ways on one or both surfaces of the glass. Coatings 2 and 3 may be connected through an adjustable resistance, or spark gap 4 and 5, which may be within or without the tube. A single coating may discharge on to a cap attached to the leading-in

* See also footnotes, pp. 65 and 183

† Brit. Patent 20,140/1900.

wire 7, or on to an earthed wire optionally without resistance or spark gap; or two coatings may be earthed. The conductive coatings may be formed by plating the glass.

A similar principle has been utilised by C. T. Ulney of The Westinghouse Lamp Company of America * for the electron tube. The presence of a positive charge upon an ionic tube causes the exterior of the envelope to be bombarded by negative electrons of the external atmosphere, etc. Since their mass and velocities are small the effect is not great. With the electron tube however the presence of the negative charge causes the external envelope to be bombarded by external positive charges which, being of comparatively large mass, may overheat and crack the envelope. The above company therefore coat the internal and external walls of the tube with a metallic layer, or metal may be deposited upon the glass. These layers are in electrical connection either *viâ* the anode lead or directly by wires *viâ* the glass bulb itself. The outer layer serves

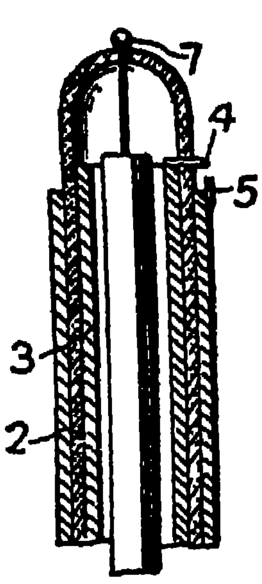


FIG. 46.—Winter's Protective Shields.

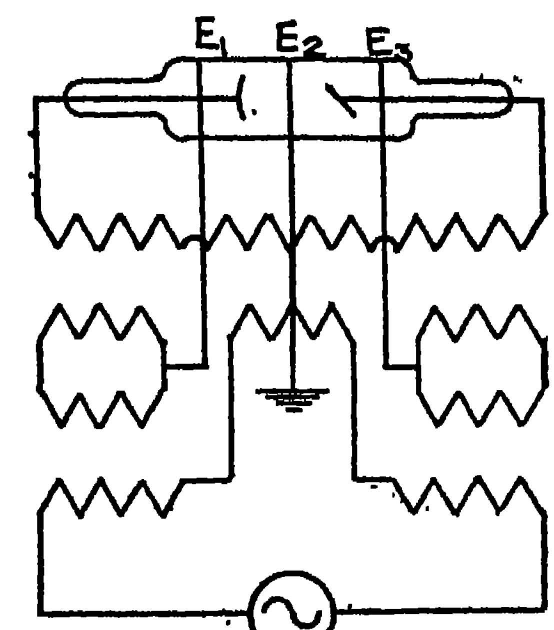


FIG. 47.—Desguisne and Dessauer Method of Distributing Potential over Envelope.

to prevent the glass from being bombarded and at the same causes the neutralisation of the internal and external charges. The coatings also serve to remove the region of abrupt electrical charge from the anode neck to the bulb, where it is distributed over a wider area with beneficial results as regards heating effects and resultant stress of expansion. Such an arrangement does however tend to cause local overheating due to sudden change from conductive metal to non-conductive glass (see p. 54).

A somewhat different method has been adopted by C. Desguisne and F. Dessauer † who introduce a number of electrodes, $E_1$, $E_2$ and $E_3$ (Fig. 47), kept at different potentials by connection to the various steps of a Dessauer transformer (Chapter IV.). Such accessory electrodes serve to produce a uniform fall of potential throughout the length of the envelope.

* Brit. Patents 207,807/1922 and 207,808/1922.
† Brit. Patent 207,262/1922.

An analogous arrangement has been utilised by the Philips Company in their metal tube.*

In this (Fig. 48), the fall of potential from anode to envelope walls is regulated by the use of several metallic shields, 30, 25, 26, for the anode and 27, 28 for the cathode. These serve both to prevent electronic bombardment of the glass and metal joint and to maintain a progressive potential change. Each shield is then connected *viâ* the glass wall to the appropriate tappings of the high-tension transformer 39 exciting the tube.

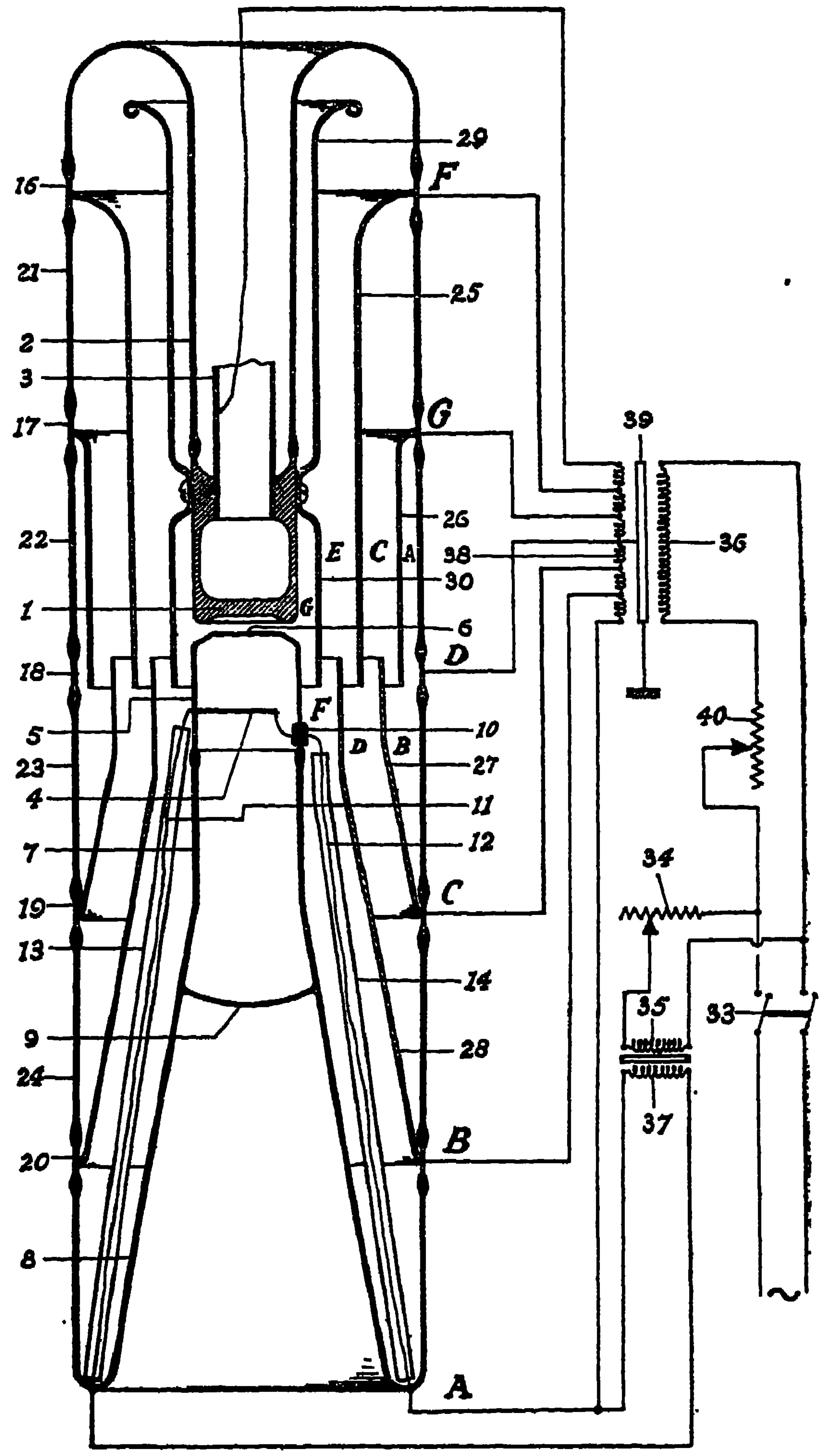


Fig. 48.—Philips Method of Distributing Potential over Envelope.

Whilst such stress distribution may be very efficient, the form and position of the accessory shield electrodes must be very carefully designed or discharges occur between the main and accessory electrodes, and the discharge, so becoming localised, overheats and ruptures the tube wall, or alternatively, affects the focus of the radiation from the tube.

The overstressing of the tube walls is much minimised if the X-ray tube is oil-immersed, as the oil serves to prevent partially abrupt dielectric alternations with consequent local ionisation and discharge (corona). Conversely the presence of conductive metal tends to accentuate these stresses.

Dauvillier † has suggested a novel method of overcoming the stress upon the tube walls by use of a double envelope $W_1$ and $W_2$, each wall being

* Brit. Patent 242,946/1925.
† French Patent 546,763/1922.

separated by a high vacuum (Fig. 49). Whereas the internal wall acquires a high charge, the outer wall, by virtue of the vacuum and the re-entrant cathode sleeve, remains neutral and external irregularities cannot cause local discharge. As however the double wall is essentially a Dewar flask, as used in the well-known Thermos flask, the tube is not directly applicable to thermionic tubes, as the heat of the filament would tend to accumulate. If however a metal tube is used, as shown in the figure, such heat is radiated to and radiated from the metal of the tube. The method is directly applicable to ionic tubes with water or other cooling of the anode and also to valve tubes.

*Form of the Envelope.*—Coolidge has stated* that a thick glass bulb is preferable to a thin bulb, as electrostatic surges of energy liable to crack the bulb do not so easily occur with a thick as with a thin bulb.

Whereas the spherical form of bulb is that most commonly seen, such

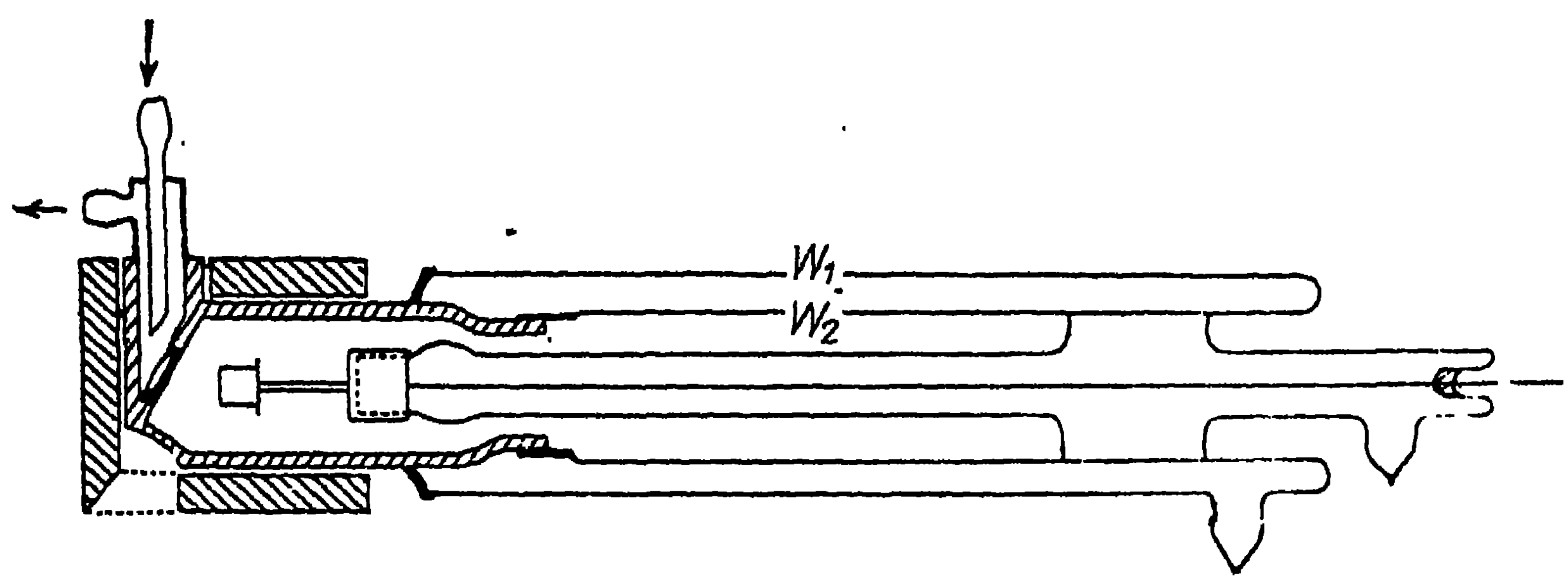



FIG. 49.—Dauvillier's Double-walled Tube.

a form of bulb suffers from the absence of mechanical strength. If this sphere is too small it is found the heat from the anode, concentrated upon the smaller surface, tends to unduly heat this. As the size of the bulb is increased so the heat per unit area becomes smaller, but at the same time the bulb becomes cumbersome and unduly fragile. As secondary results the containing tube box or holder has to be increased in size, with consequent increase of cost and weight of protective material as lead rubber. A smaller bulb also gives better radiographic definition, as it allows the diaphragms to approach nearer the focal spot and also the nearer approach of the object to be X-rayed.

Whilst the heat developed in the tube is, in the electron tube, due to both anode and filamentary cathode, the former overshadows the latter. If the anode is well cooled, as by water circulation in the Müller electron tube and the Lilienfeld tube (Fig. 50), the necessity of a large envelope is not so imperative and the tube can take the ovoid form shown, which has advantages of economy of space with greater mechanical strength.

* Brit. Patent 155,345.

FIG. 50.—Lilienfeld Tube.

Practical difficulties in sealing off small bulbs arise. Whenever glass is fused, as for sealing, a certain amount of gas is always evolved. With a small bulb the lowering of the vacuum, in consequence of this release of gas, is far greater than with a large bulb. Because of this evolution of gas the tube is allowed to remain in connection with the vacuum pump some little time after actual fusion of the glass before the seal is finally closed.

*Function and Coloration of the Envelope.*—The action of the envelope has already been stated to be of considerable importance in the operation of ionic X-ray tubes, since it provides the greater part of the electrons, produced by ionic bombardment of the glass.

That these do not only arise from the metal electrodes and that electrons so produced are not of prime importance as the source of electrons, is shown by the fact that tubes have been successfully constructed in which the electrodes were entirely without the envelope in the external atmosphere. Such a tube was described by Arsonval * in 1896 and a patent for a tube of this type was obtained by W. J. Robinson † in 1917. Such tubes are only suitable for small outputs and soft radiation. The flow of any considerable electrostatic flux and current *viâ* the glass dielectric in the region of the electrodes causes overheating and rupture. With high potentials the electrostatic stress is concentrated across the glass and an excessive stress is produced between the glass and electrode.

The ionic bombardment of the tube wall causes electrolysis to occur in the glass itself. This results in the breakdown of the chemical constituents of the glass. As a result the manganese dioxide in soda glass, introduced to remove the green colour of ferric salts (always present), is converted to manganates of a violet colour which is always well seen in an old X-ray tube after considerable wear. Such coloration may be removed by heating the glass, which causes the manganates to revert to their original chemical form.

Tubes of lead glass similarly show a brown coloration due to the decomposition of lead salts to oxides by electrolysis.

The glass of an X-ray tube may also become blackened. This is due to the walls attracting negatively charged particles sputtered from the cathode. This thin film of very finely divided metal displays very considerable occlusive powers and results in gas being abstracted from the tube atmosphere, so causing the tube to become extremely hard.

Coolidge tubes are wrongly stated not to undergo colouring effects, although often showing the darkened effect due to metal volatilised from the electrodes and particularly the cathode.

* Imbert and Bertin-Sans, *Comptes Rendus*, 122, p. 605, 1896.
† Brit. Patent 112,101/1917.

In however a very much used Coolidge tube, a violet coloration can be discerned.

It appears that the whole active hemisphere of the tube, *i.e.*, that portion submitted to X-radiation and lying before a plane passing across the target face, undergoes the normal violet coloration of an X-ray tube. This change is attributed to chemical change of the manganese salts actually induced by X-radiation. It is well known that X-rays can directly induce chemical change and this fact is made use of in many chemical intensimeters, for example, the colour changes induced in mercury salts are used in the Schwartz intensimeter. X-rays are also used to change the colours of rare stones, to increase their value. A similar change appears to be directly induced in the manganese salts of the Coolidge-tube glass where this is submitted to X-radiation.

A ring much darker than the other violet coloration will often be found between planes just behind the anode. It would seem the molybdenum, of which the anode stem is formed in this region, is the cause of greater discoloration than the tungsten of the anode. It should however be remembered that this region is that over which abrupt change from negative to positive charge occurs over the envelope, which may influence the degree of coloration due to electrolysis.

## THE ATMOSPHERE OF THE X-RAY TUBE

Ionic and electron tubes are chiefly characterised by the different degree of their vacua.

In the ionic tube the vacuum is, in terms of high-vacua technology, relatively high and ranges from about ·01 mm. of mercury for a "soft" tube to ·001 mm. of mercury for a "hard" tube. The terms "soft" and "hard" are relative only and there is no sharp separation of soft and hard tubes.

These terms are an approximate measurement of the voltages at which the tube resistance is broken down. Since this voltage measures and exactly determines the speed of the electrons producing the radiation and this in turn determines the wavelength or quality of the radiation and the penetration, one may say that a soft radiation is of low penetrative power and a hard radiation of high penetrative power.

In the electron tubes, such as the Coolidge tube, the vacuum is very considerably greater and is specified by Coolidge as being below ·0006 mm. of mercury and as low as ·00005 mm. of mercury.

At such low pressures gas ionisation no longer plays a part in conduction, as the chance of an electron striking and ionising a gas atom is remotely small.

More recently Philips have shown that there is, between the high pressure of the gas tube and the low pressure of the Coolidge tube an

intermediate region in which, whilst considerable gas is present, ionisation and irregularity of discharge can be prevented by ;

(*a*) Suitable choice of the gas.

(*b*) The use of a flat target not favouring ionisation discharge.

(*c*) The close apposition of the filament cathode and target.

For the gas, hydrogen or helium is chosen. These gases appear to resist ionisation under the above conditions, and it is stated will actually do so up to pressures of 1 mm. of mercury. The close apposition of the filament to the very flat target apparently does not allow a sufficient distance for the electronic path for collision with gas atoms and ionisation to result.

The exact function of the gas in an ionic X-ray tube is still very largely undecided. Many authors have considered that the gas in the tube is always to some extent ionised and contains free electrons, possibly produced by the generalised radio-activity of the earth. The application of a sufficient potential causes these electrons to acquire sufficient velocity and energy to ionise further gas atoms they encounter in their course. The electrons produced by such " shock ionisation " then constitute the current *viâ* the tube and, losing their energy by impact at the tube's anode, this energy is converted to X-radiation and other radiant energy.

That there is always some free electrons present in a gas to commence this shock ionisation has been shown by A. H. Compton and Foulker,* who found that an X-ray tube surrounded by lead becomes hard as compared to an open tube. The inference is that the lead intercepts the radium $\gamma$-rays which cause ionisation of the gas in the tube, and the tube hardens, since any free electrons present are slowly attached to gas atoms. As a consequence when a potential is applied the electrons, necessary to produce gas ionisation, are very few.

The discharge of an X-ray tube can be controlled by other ionising agents, as ultra-violet light. In the past it has been proposed to actually introduce radium salts in order to provide electrons to inaugurate the shock ionisation of the above theory. Such tubes have been introduced by Jahoda† in France and Gundelach‡ in Germany, but do not appear to have been of great value in practice.

In the above view there is no part played by the glass envelope except to enclose the vacuous space. Also the electrodes play no part in the actual ionisation and production of electrons, merely serving for the application of the necessary potential difference and, in the case of the anode, or anticathode, suddenly to arrest the electrons derived from the gas and so convert the energy of the electrons to radiant energy.

A more recent view is that of Dauvillier, who considers that the

* *Gen. Elect. Rev.*, 26, p. 755, 1923.

† French Patent 476,881/1914.

‡ Röntgen Societies' Tube Exhibit No. 62.

residual gas of the tube only plays a negligible part in the total production of electrons and that whilst the electrodes take part in electron production the chief source of electrons is by ionic bombardment of the tube walls. That the electrodes do not give rise to electrons to a great extent is proved by the tubes having external electrodes only (see p. 71).

Dauvillier * considers that the production of electrons does not result by shock ionisation of gas by residual electrons, but by the bombardment of the tube walls by electrons emitted from the cathode as a consequence of the application of a sufficient potential. These electrons cause ionisation of the residual gas and the ions so produced bombard the walls of the tube, producing further electrons accompanied by fluorescent effects. It is these electrons which constitute the current *viâ* the tube. The ions so produced then bombard the walls and aluminium cathode, so producing further electrons.

The actual production of further electrons by shock ionisation during the passage of electrons *viâ* the gas from cathode to anode, as upon the older view, would appear to be relatively unimportant when the relatively small volume of gas transversed by the cathode ray bundle of small cross-sectional area is considered.

*Nature of the Gas.*—The residual gas of an X-ray tube may be merely residual air (oxygen and nitrogen chiefly) or a special filling of nitrogen, hydrogen, or an inert gas as helium or argon. In the case of air filling doubtless the oxygen is soon removed by oxidation of the electrodes and the tube becomes virtually a nitrogen tube.

The colour of the negative glow at the cathode is dependent upon the residual gas and is blue for nitrogen, yellow for oxygen and rose for hydrogen.

Tubes have been commercially produced containing inert gases, as helium or argon, and for which special virtues have been claimed.

The disintegration of the cathode known as " sputtering " is dependent upon the nature of the gas filling and is the more, the greater the atomic weight of the gas. This one might expect, since the positive ion is an atom from which one or more electrons of comparatively negligible mass have been removed. The heavier the gas atom the heavier must be the ion, and it follows the greater destructive power of this ion when it bombards the cathode.†

Hydrogen would therefore appear to be a more suitable gas than helium, except for its power of entering into chemical combination with the electrodes and its considerable power of being occluded by the electrode metal and so removed from the sphere of active ionisation.

* This view is not generally held, see footnote, p. 65.

† Daumann states (in a personal communication to the author) that the energy of collision is more dependent upon the electrical charge than upon the atomic mass, *i.e.*, an atom of light mass which has lost two electrons (ion) may be more destructive than a heavy atom which has lost only one electron.

Argon, of comparatively high atomic weight, would appear to be unsuitable on account of the greatly increased sputtering effects.

Siegbahn* has given the following table for pressures (in bars) at which soft, medium and hard X-rays are produced ;

| | Gas. | | | | | |
|---|---|---|---|---|---|---|
| | $H^2$ | He | $O_2$ | Air | $CO_2$ | A |
| Soft .. .. | 21 | 38 | 7 | 12 | 7 | 12 |
| Medium .. | 11 | 22 | 5 | 6 | 5 | 7 |
| Hard .. .. | 7 | 11 | 4 | 4 | 4 | 4 |

From this table helium would, for equal pressure, appear to render a tube hard as compared to hydrogen, whilst argon to render a tube soft.

Other things being equal, an argon tube would be more suitable for the production of radiographic and radioscopic effects showing great detail due to soft radiation. Similarly a helium filling would be more suitable for producing highly penetrating radiation. As however an equal effect in either direction can be obtained by modifying the degree of a more common gas as hydrogen, no great advantage appears to result from such fillings, necessitating a more involved technology of manufacture, in order to deal with such expensive inert gases. Further we have the objection of increased cathodic sputtering due to these gases.

For the argon tube it has been claimed the regularity of discharge is improved, apparently owing to avoidance of pressure alteration due to chemical and occlusion changes. Should sputtering result however the occlusion removal of gas would doubtless be increased.

A more rational claim, from the figures of Siegbahn, would be that the argon tube allows the use of very heavy discharges at high voltages for flash photography, where the cost of tube renewal is unimportant, as compared to the obtainance of the object desired.

The pressure of gas within an X-ray tube may be intentionally or otherwise altered by various effects, of which the most important are ;

(1) Physical occlusion of the gas by the metal of the electrodes rendering the tube hard.

(2) Overheating of the electrodes, by overloading, will cause occluded and dissolved gas to be evolved and render the tube soft. This will give a greater value of the current *viâ* the tube but the quality of the resulting radiation is more poor, *i.e.*, more soft and often unsuitable for practical radiographic purposes.

* M. Siegbahn, " Spectroscopy of X-Rays," p. 81.

(3) Gas may be removed by its chemical combination with the metal of the electrodes. In an air filling the oxygen so removed produces oxides and the nitrogen nitrides. Such compounds are seen in the dark rings upon the cathode of an X-ray tube. These layers of oxides or nitrides, being very thin, may give rise to interference colours.

(4) Gas may be removed by occlusion upon the wall of the tube. According to the view of Langmuir, such gas is held in a state of loose chemical combination by the residual valencies of the atoms of the tube walls. This causes the tube to harden. A tube so hardened may be softened by heating it in a bath of sand, which causes the occluded gas to be driven off again. Such a softening is however usually only temporary.

It has often been stated that gas is removed by its being actually driven into the glass by virtue of their high velocities and so entangled amongst the atoms of the glass wall. Such a view was put forward by Campbell Swinton.* This view was largely based upon the fact that glass of an old X-ray tube on heating gives off gas in the form of bubbles in the glass. A somewhat similar view was held by Gouy.† Soddy and Mackenzie ‡ have however shown that if the tube has been filled with helium the gas evolved from the glass is not helium. These bubbles are therefore not due to the gas ions being driven into the gas and would appear to be gas merely evolved by chemical change in the glass, induced by heating.

It has also been stated that not only is gas so driven into the glass but that gas can even be driven completely through the glass and the tube so rendered hard. Such a view is incorrect. The ions on the X-ray tube are entirely the same as the "canal rays" of discharge tubes. It has been shown that such rays cannot penetrate more than ·015 mm. of glass, and it is therefore extremely unlikely that ions would pass *viâ* glass 1 or 2 mm. in thickness at the voltages normally used to excite such tubes.

(5) When the electrodes are sputtered the power of the metal to occlude gas is greatly increased, owing to the greatly increased surface of metal due to the fine state of division. The removal of gas may then be so extreme that the tube will no longer allow the passage of discharge, unless electrons are produced in some other way, for example, a heated filament. The effect is used to obtain the desired high vacuum of the electron tube. Such sputtering may cause a gas tube to work very erratically.

It is useful to know that a tube which, by overloading, has been rendered unusefully soft by disengagement of gas from the electrodes, may be easily hardened by use of this property. The tube is used for brief periods connected so that the normal anode is now the cathode. The anode being of high atomic weight easily sputters, and if the tube is

* *Proc. Roy. Soc.*, 79, p. 134 (1907).
† *Comptes Rendus*, 122, p. 775, 1896.
‡ *Jour. Rönt. Soc.*, 4, p. 46, 1908.

then allowed to rest, the sputtered metal slowly absorbs the excess of gas. The operation requires some judgment to produce a good result and there is some danger of fracture of the glass envelope.

(6) The possibility of disengagement of gas by the electrolysis which occurs in the glass of the tube should be recognised.

## METHODS OF CONTROLLING THE DEGREE OF VACUUM

The causes which operate to cause variation of the degree of vacuum of an X-ray tube as just enumerated, renders it necessary to have means to regulate and to correct these changes. It must be realised that since the action of the tube is dependent upon gas ionisation, to produce further ionisation either by ionic collision in the gas itself or by ionic bombardment of the tube walls or cathode, the action will be very dependent upon the gas pressure.

Upon the kinetic theory of gases the pressure is merely a measure of the number of gas molecules per unit volume and this number will determine ;

(1) The number of ionising collisions per unit length of path.

(2) If the pressure is too great the free mean path will be smaller. There will therefore for any given applied potential be a certain minimum free mean path necessary to allow any electron to obtain sufficient velocity and kinetic energy to cause ionisation, over which it must pass before collision with a gas atom. Otherwise its energy is lost by collision before it has reached the value necessary for successful ionisation.

We may classify the methods of varying gas pressure (which are chiefly to cause increase of pressure) as follows ;—

(1) *Chemical methods*, in which gas is evolved by chemical changes.

(2) *Occlusion methods*, in which gas is evolved from a suitable occluding medium.

(3) *Replenishing methods*, in which gas is caused to enter the tube from the external atmosphere, either by gaseous diffusion *viâ* a suitable metal, or, by direct entry under the control of a suitable valve.

Usually these methods involve a specific operation, but methods are also utilised in which the pressure variation occurs automatically.

(1) *Methods Based on Chemical Action.*—This is the oldest method of pressure variation. It was the custom in the very early days of X-radiology, to introduce red phosphorus into an annexe to the tube. This absorbed oxygen to form oxide. When the tube became hard this annexe was heated and in consequence the chemically combined oxygen was released. Very many other chemical compounds were later used to replace the red phosphorus, which may be summarised as ;

(1) Caustic potash (Crookes and the British Thomson-Houston Company, Brit. Patent 13,966/1900).

(2) Silver nitrate (Böhm, Brit. Patent 22,794/1896).

(3) Potassium chlorate (Stearne and Topham, Brit. Patent 13,109/1897).

(4) Organic bodies (Glew, Brit. Patent 25,659/1897; Robinson (paraffin wax), Brit. Patent 25,047/1905).

A more recent method of this type is that of Jackson (Brit. Patent 182,195/1921) of the British Scientific Instrument Research Association. In this tube (Fig. 51) two annexes are present. One contains boron nitride or other nitride, which is heated by an electrical filament, so evolving nitrogen and softening the tube. The other annexe contains boron, or titanium, which when heated, either electrically or by passage of the tube discharge between it and the cathode, forms nitride and reduces the pressure. A similar method was used in 1920 by Mutscheller,* who employed nitrides of aluminium, barium or thallium.

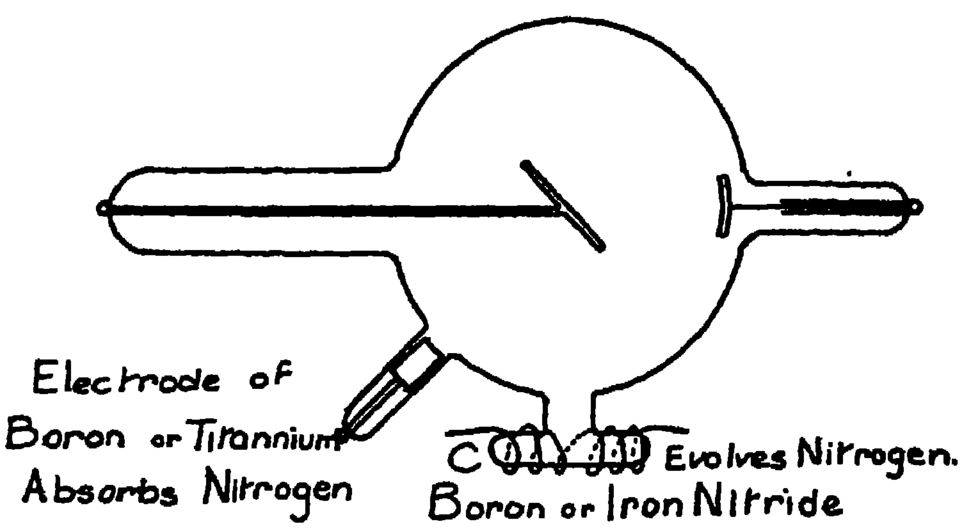



FIG. 51.—Jackson Nitride Tube.

In such processes a reversible chemical action occurs as ;—

$$N_2 + B_2 \rightleftarrows 2BN$$

and the first proposal to use such a reversible, and moreover a balanced chemical reaction, is that of [illegible]lemann (French Patent 465,503/1913; Brit. Patent 27,599/1913) who heated electrically, or by other suitable means, calcium or barium carbonate to give a reaction ;

$$CaCO_3 \rightleftarrows CaO + CO_2$$

the direction of the reaction being dependent upon the temperature, *i.e.*, if heated, $CO_2$ is disengaged and the tube softens, whereas, in cooling, $CO_2$ is absorbed and the tube hardens. By regulation of the temperature of the heating filament any desired degree of vacuum could be maintained.

An ingenious automatic softening device has been protected by the B.T.H. Company (Brit. Patent 13,966/1900) in which potassium hydroxide is placed behind the target in line with a hole in the target. As the tube hardens it is stated the cathode ray passes *viâ* this hole and heats the chemical with the disengagement of gas.

A more certain method of operation is that of Caldwell (Brit. Patent 29,839/1912) for use in valve tubes, in which a solenoid is inserted in a recess in the tube and caused to deflect, at will, the cathode beam upon suitably situated sodium formate.

The objection to all such methods of softening X-ray tubes is the risk

* *Arch. Electr. Med.*, 28, p. 325 (1920); *Amer. Jour. Rönt.*, 7, p. 261 (1920).

of fracture of the glass. Whilst the method commonly known as the " condenser method " (*q.v.*), as now commonly used, offers much less risk of fracture, a still more convenient method is that in which the chemical is heated by means of a wire filament either internal or external to the tube (Fig. 51), a method originally introduced by Rodde.

(2) *Methods Based upon Gaseous Occlusion.*—In this method, gas to soften the tube is provided by heating some substance within the tube, which then evolves gas not by chemical dissociation but by release of occluded gas. A very early attempt at this method is that of Krouchkoll (Brit. Patent 7,838/1902), who placed in a tube annexe glass capillary tubes, from which adsorbed gas could be driven off by heating.

Paschen (Brit. Patent 10,878/1908) inserted wood charcoal, the occlusive properties of which could be varied by heat to soften the tube or by cold to harden the tube. The use of liquid air to harden the

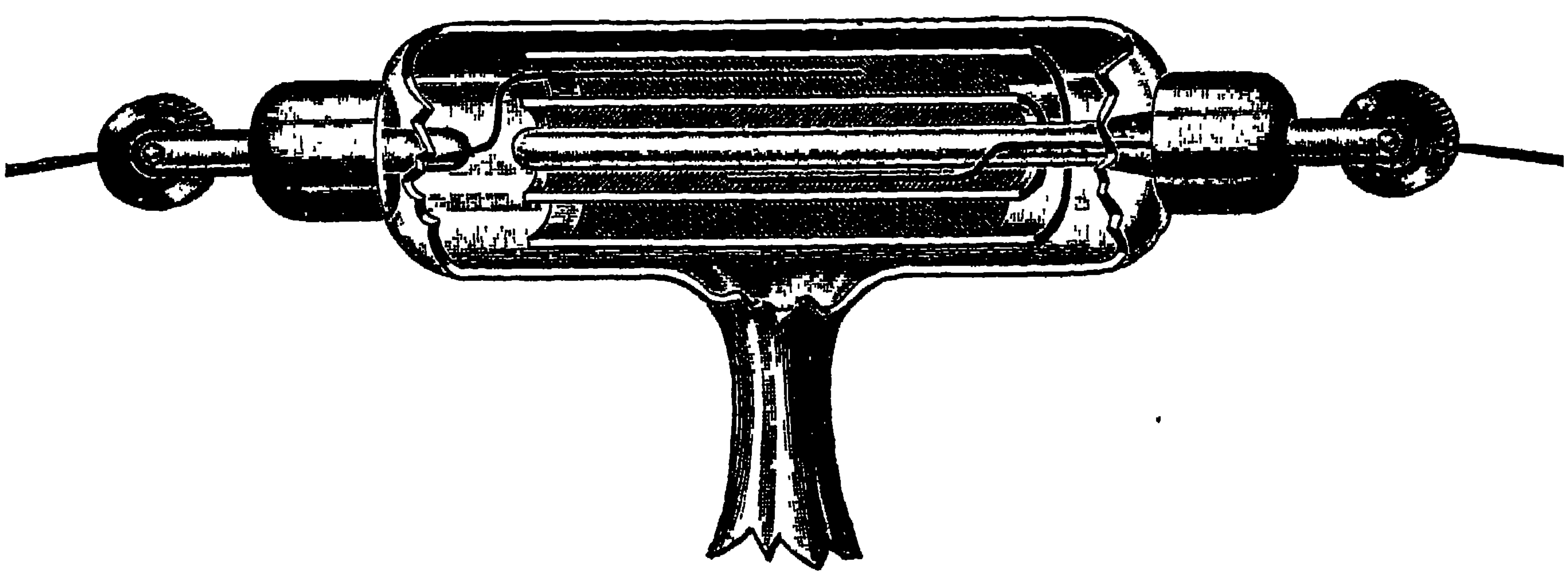


FIG. 52.—" Condenser " Softening Device (Messrs. Gundelach).

tube is specified, a method somewhat inconvenient in normal radiological practice.

The occlusion method was perfected in the hands of Gundelach, and his form of softening device is employed upon the majority of present-day gas tubes, under the name of " condenser softener," shown in section in Fig. 52.

A small condenser is formed by connecting external electrodes to internal metallic cylinders, so constituting a condenser. Between the plates of this condenser some gas-occluding substance, as asbestos, mica, carbon, or glass wool, is inserted.

When the tube becomes hard the regulating, or " condenser wires " at each end of the device, are moved so as to short-circuit the tube discharge *viâ* the condenser device. Brush discharge then occurs between the plates of the condenser, and, the asbestos so being heated, gas is evolved.

A further occlusion method, which does not appear to have come into practice, is that of Gover and Cooke (Brit. Patent 13,109/1897), in which

a carbon filament, capable of being heated, is inserted into the tube. When heated such a filament evolves gas and it is undoubted the filament also gives off electrons by the Edison effect. A similar method was used in 1898 by Bonetti,* who employed a platinum filament, and later by Morton in America.

The condenser method of softening is very convenient and very largely used, and its only defect is that the quantity of occluded gas becomes ultimately completely used up, in which respect it is inferior to the methods later to be described.

It further suffers from the inconvenience that the regulating wires have to be moved by hand, when it is desired to soften the tube enclosed in an unwieldy tube box. This can be overcome by weighting the regulating wire, so that it is by this weight normally away from the softening position, but can be brought to this position by pulling a string. This method of operation is quite convenient but in turn introduces the defect that the wires, being close to the tube box walls, are very liable to cause irregular action and sparking of the tube, due to discharge occurring between the wire and the wall of the box.

A further method of use is to set permanently the regulator wires so that, when the tube hardens, the distances are such that a discharge automatically passes in order to soften the tube and again ceases when, the tube having softened, the discharge then again occurs more readily between the normal tube electrodes, than across the external gap formed by the softening wire.

(3) *Replenishing.* (*a*) *Osmosis Method.*—This method was first introduced by Villard and Chaubaud,† in consequence of the experiments of St. Claire Deville upon the passage of gases by diffusion *viâ* iron and platinum. It was also introduced independently by Winklemann and Straubel of Jena. It appears to have been first introduced into England by Cossor (Brit. Patent 11,829/1905), several years later. It is now well known that platinum and particularly palladium have, when heated, the power to allow gases to pass *viâ* them. To utilise this effect a tube of platinum or palladium is sealed into the X-ray tube. When the tube hardens the osmosis device is heated and hydrogen from the flame or external atmosphere diffuses *viâ* the metal of the tube into the X-ray tube and causes it to soften. At the same time there is a passage of gas from the tube to the external atmosphere but, since the pressure of the latter is much greater than the pressure of the internal tube atmosphere, more gas passes into than out of the tube.

The gas which enters is hydrogen from the breakdown of hydrocarbons of the flame atmosphere. In the case of a hydrogen tube, were this not the case, the tube would tend to harden.

* *Comptes Rendus*, 126, p. 1893, 1898.
† *Comptes Rendus*, 126, p. 1413, 1898.

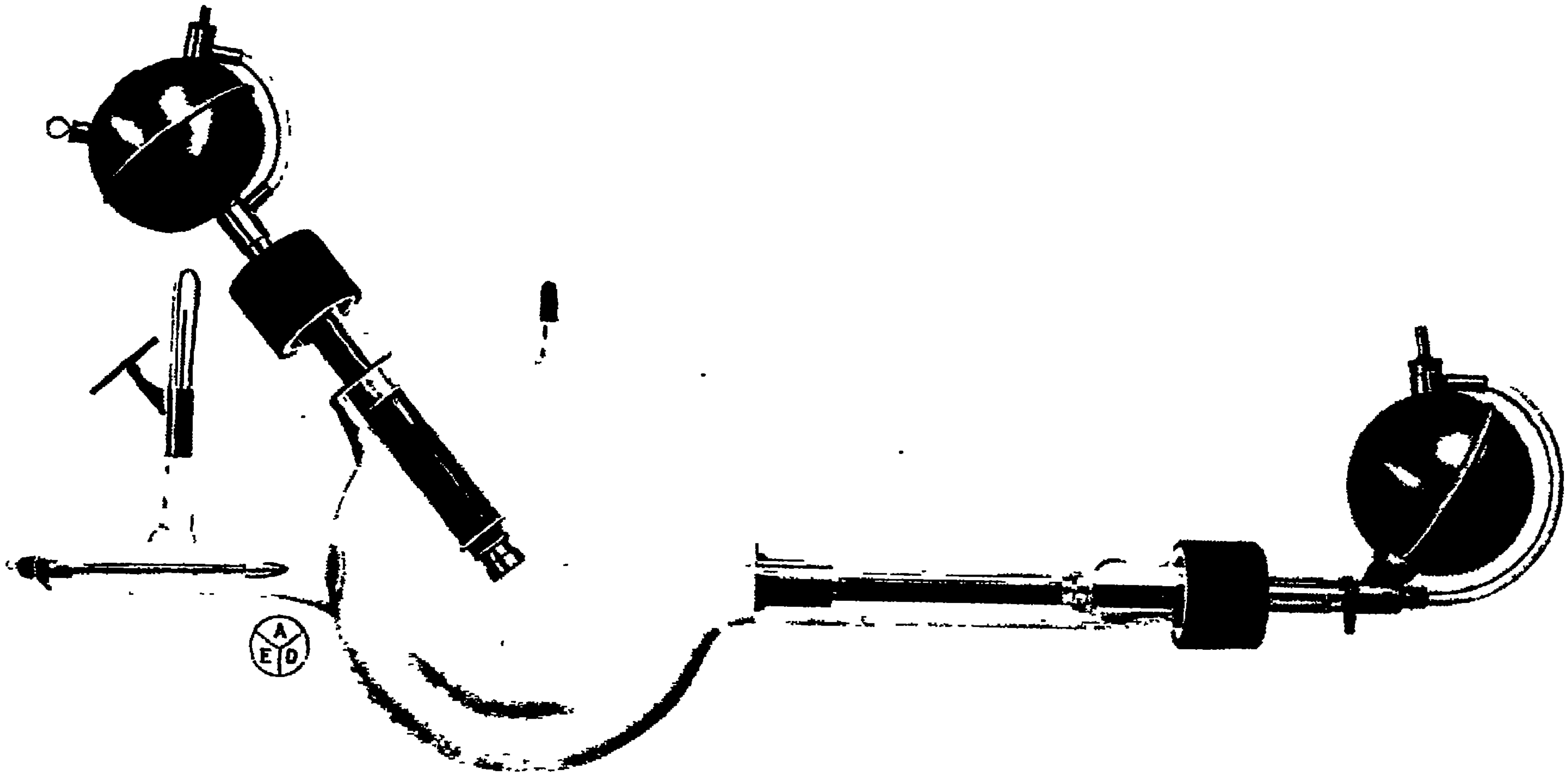



FIG. 53.—Boiling Water Tube with Osmosis Softening Device (A. E. Dean).

To face p. 80.

Regnaud (Brit. Patent 8,250/1912) has used a less common method in which hydrogen or coal gas is passed into a hollow anticathode to the back of the target and, when this becomes heated, diffuses directly *viâ* the target metal.

The osmosis method forms the basis of the well-known Snook hydrogen tube, at one time much used in England. In this tube (Brit. Patent 100,090/1916), two osmosis tubes are sealed into the X-ray tube (Fig. 54). One tube is of platinum in an enclosed atmosphere of hydrogen and the other of palladium, externally open to the air.

If the tube is hard the platinum device is heated by an auxiliary discharge and, as a consequence, hydrogen from the reservoir passes into the tube and causes it to soften. If the tube is soft the palladium tube is heated and hydrogen diffuses out of the tube and the tube in consequence hardens.

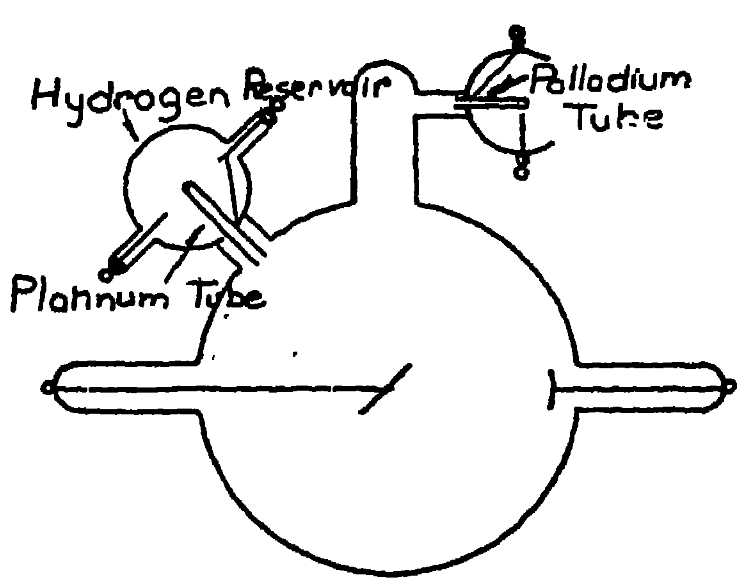



FIG. 54.—Snook Tube.

The great advantage of the osmosis softening device over the condenser device is that in spite of its still more inconvenient operation, it very readily allows distant and automatic control.

Such a method of distant control was introduced by Holtzknecht, in which a gas jet is arranged (with a by-pass jet) to play upon the softening tube (Fig. 55A). The gas supply to the main jet was controlled by a small valve (Fig. 55B), operated by finger pressure and connected by rubber tubing. The opening of this valve allows the passage of gas to the jet which, ignited by the by-pass, causes the flame to play upon the osmosis tube and so to soften the tube.

Such a form of distant control has been much used in therapeutic work where the operator is behind a protected screen. Müller has utilised the alternative spark passage of a hard tube to directly ignite the gas burner of an osmosis softening device.

It is always advisable to soften a tube by an osmosis regulator whilst the tube is in action, as rapid over-softening can easily occur.

(*b*) *Direct Entry Method.*—This method, due to Bauer (Brit. Patent

15,171/1912), has been extensively employed in England, but not to the same extent as the condenser method.

The Bauer device (Fig. 56) consists essentially of a glass manometer provided with a side limb $t^1t^2$ sealed with a dense but capillary medium *s* against the external atmosphere. The side limb communicates with the interior of the vacuum tube, but is sealed by means of the mercury of the U-tube. Pressure by a small pump, connected by rubber tubing to *q*, causes this mercury to be pressed away from the porous seal *s*, and air then slowly enters the tube by diffusion *viâ* the plug from the atmosphere. As soon as the tube is sufficiently softened the pressure is released and the mercury again seals the U-tube.

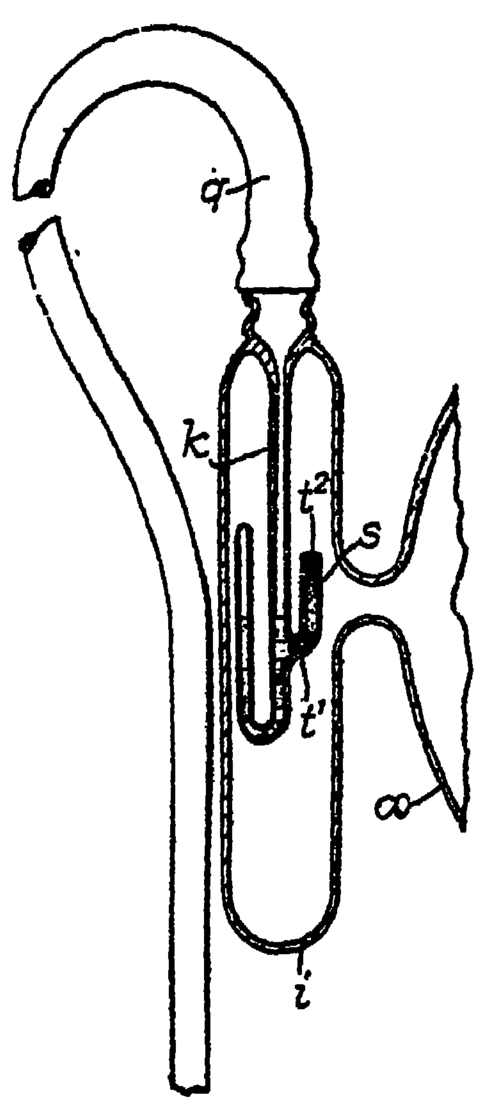


FIG. 56.

A Bauer regulator is shown in Fig. 57 in a special therapeutic tube. Two regulators are present, one of the Lindemann type (p. 78), and one of the Bauer type. This tube, used in the early days of therapeutical work, is also characterised by a large auxiliary bulb, the purpose of which was to increase the tube volume and atmosphere and, by giving a greater gas volume, so to render the gaseous pressure more stable than would be the case with a small bulb tube.

It is often stated that the Bauer device suffers from the defect that the mercury fragments if the tube has to be transported, as in Army work. The author, using such a device in a fixed couch, has never found this to occur.

Whilst a tube may easily be over-softened by this device unless it is also operated during the softening operation, it has a great advantage over the condenser softener that, by means of a rubber connection, it can be distantly operated without opening the cumbersome tube box if the rubber connection is passed *viâ* a small hole in the tube box. In this respect it is also superior to the osmosis method, as it is impracticable to utilise a flame in an enclosed and inflammable lead-rubber lined tube box. This can be overcome by electrically heating the osmosis device by a filament, but in this case there is always a risk of breakdown of insulation of the filament circuit and a direct high-tension shock along the filament connections to the operator.

Moore (Brit. Patent 9,916/1906), prior to Bauer, had suggested the use of a device of this kind capable of distant control. This consisted (Fig. 58) of an iron cylinder F floating upon mercury covering a porous cone C. The partial immersion of this float in the mercury caused the cone to be always normally covered by mercury. If however the iron float is attracted upwards by means of a solenoid S, the

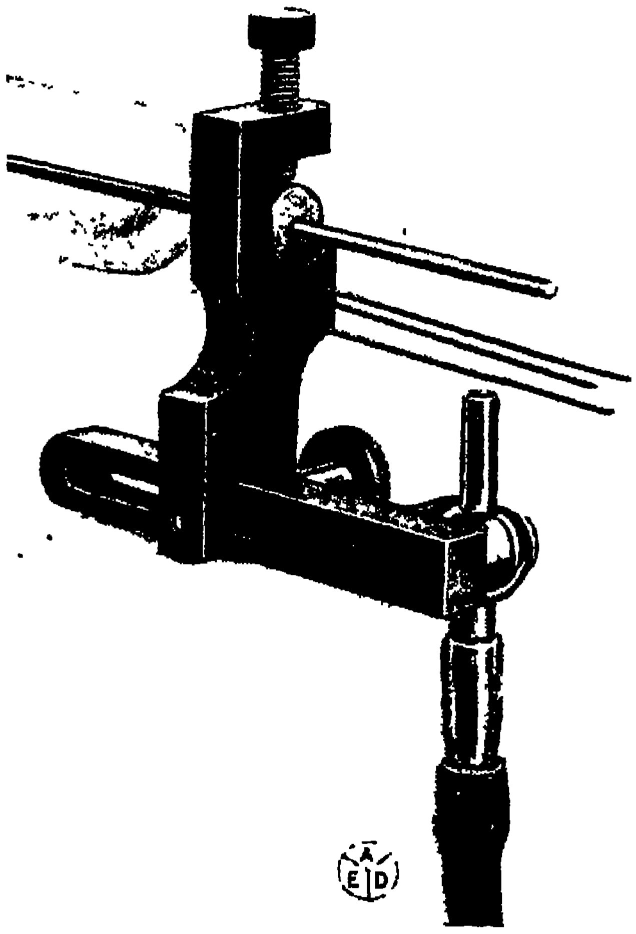


FIG. 55A.—Osmosis Regulator on Tube.

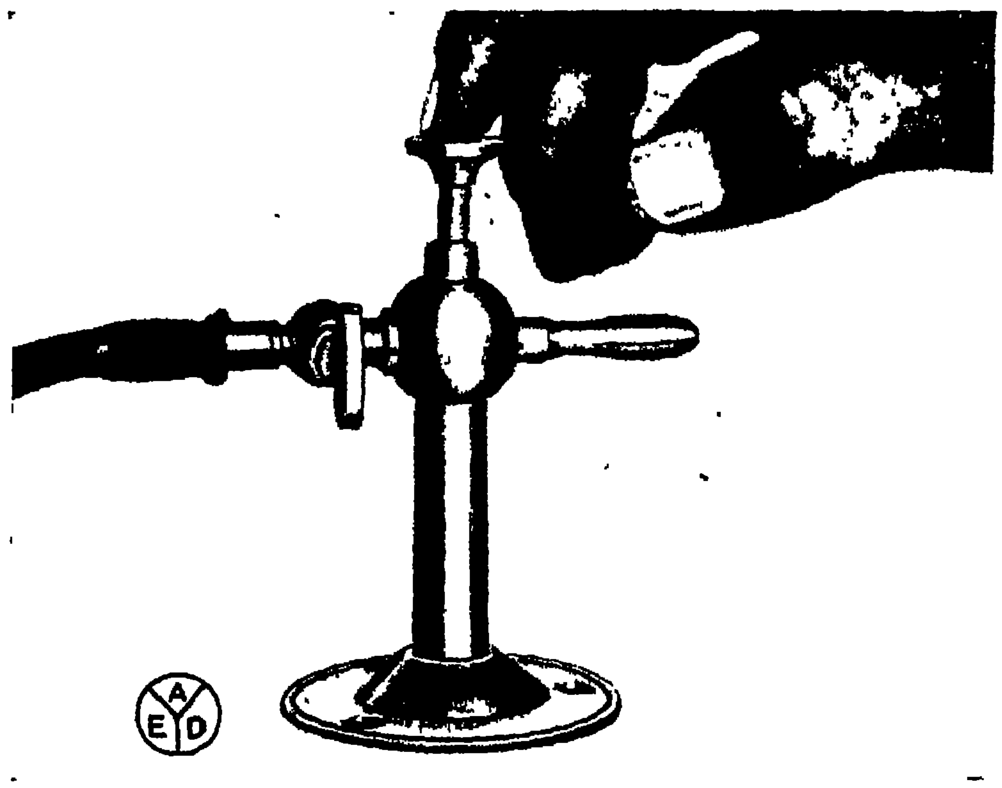


FIG. 55B.—Distant Control of Gas.

Holtzknecht Regulator.

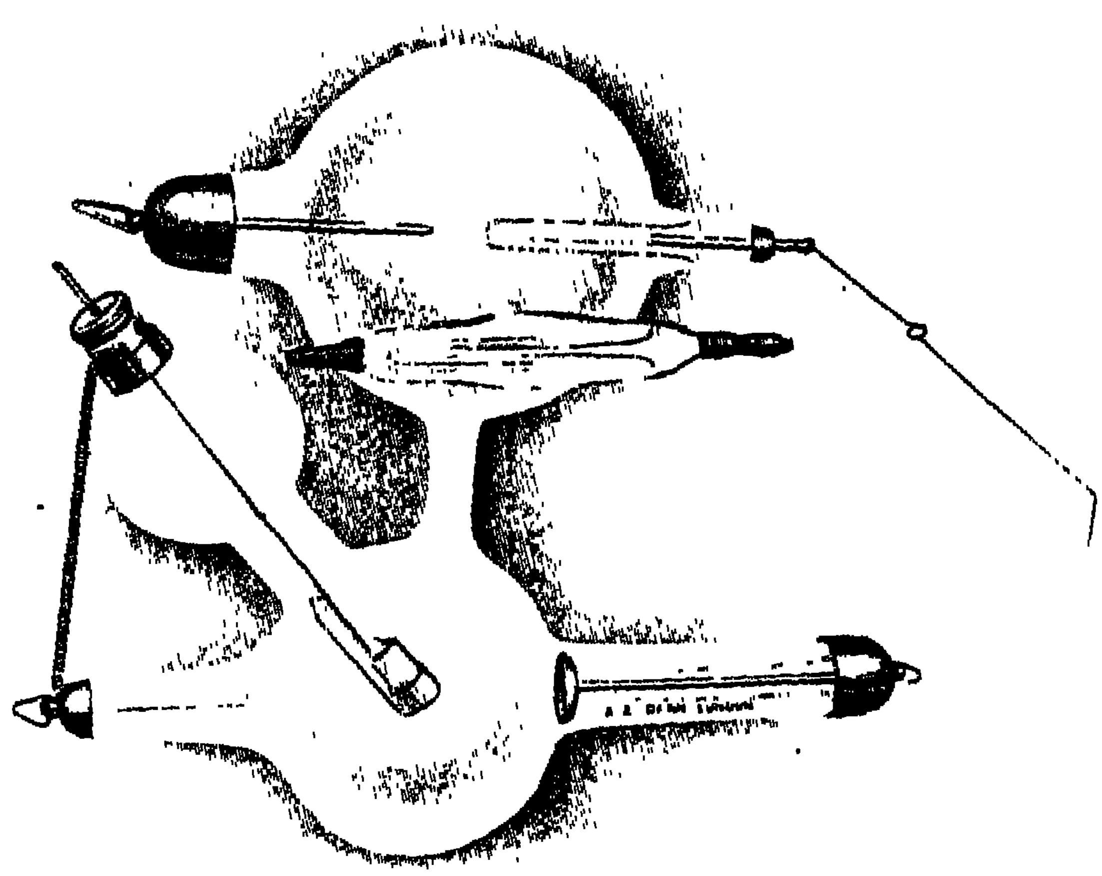


FIG. 57.—Tube with Lindemann and Bauer Softening Devices and Stabilising Bulb.

[To face p. [illegible]

level of mercury is caused to fall and the porous cone is then open to the atmosphere.

Roch (Brit. Patent 13,837/1915) (Fig. 59) uses a bulb *s*, two-thirds full of mercury and having two tubes at its centre. One tube *b* is fitted at its open end with a plug *b′*, pervious to gas, but not to mercury. A similar plug closes the inner end of the outer tube *a*, which leads to the X-ray tube. The mercury normally seals the tube *a*, but is displaced from its end when gas is forced in by the tube *b*, which may be connected to a rubber bulb. Excess of gas escapes by the orifices *s′* plugged by porous stoppers and arranged so that at least one is always uncovered by mercury irrespective of the X-ray tube's position. The porous stoppers may be covered by a membrane tied by threads. In other forms of

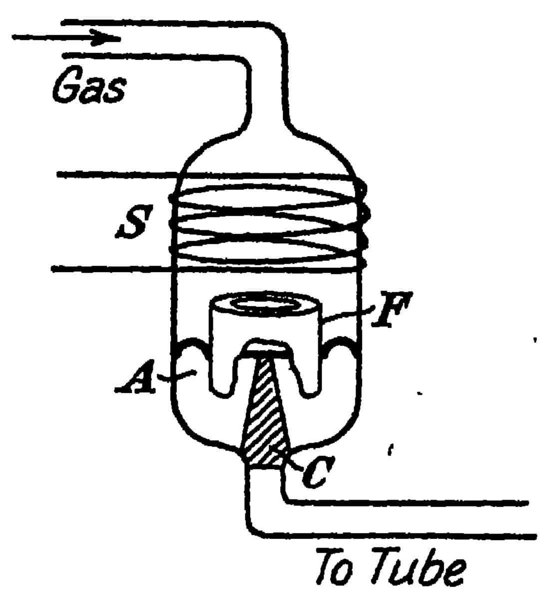



Fig. 58.—Moore's Softening Device.

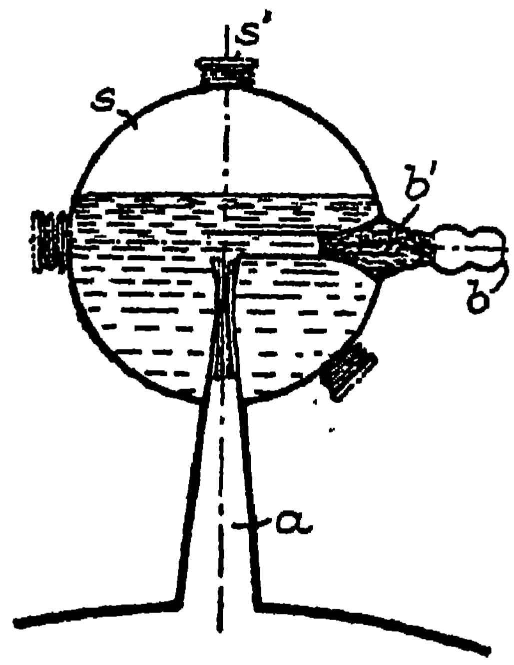



Fig. 59.

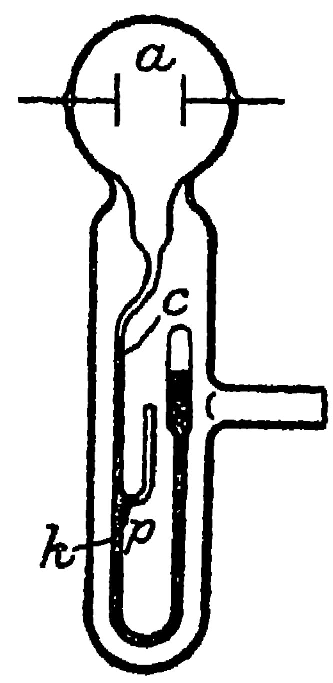



Fig. 60.—Oosterhuis and Holst Softening Device.

the apparatus the orifice *a* is closed by a valve operated *viâ* the inlet tube *b*.

A further modification of the Bauer regulator is that of Oosterhuis and Holst (Brit. Patent 139,860/1919), as shown in Fig. 60. Here the regulator at the end usually open to the atmosphere is totally enclosed in a reservoir. This reservoir atmosphere can be heated either by a filament or by a discharge between electrodes *a*. The resulting expansion of the gas causes the mercury to be pressed past the porous plug seal *k* and gas to enter the X-ray tube from the reservoir under pressure due to its expansion.

*Automatic Regulation.*—The early use of automatic regulation of tube hardness is usually assigned to Holtzknecht. Amongst the earliest attempts is also that of Moore (Brit. Patent 9,916/1906) who used the valve already described, the iron armature of which was actuated by a solenoid, fed *viâ* a transformer, by the current passing through the X-ray tube. Variations of such current were reflected *viâ* the transformer in the solenoid circuit and the valve so actuated. The difficulty of such a method is the smallness of the current *viâ* the X-ray tube combined with

the difficulty of transformer insulation at high voltages, which, in turn, renders the transformer relatively inefficient.

In the hands of Wintz and of Schreuss the distant-control method of Holtzknecht dependent upon osmotic regulation has been developed and practical forms of automatic regulators devised.

The *Wintz "Automat"* is seen in Figs. 61A and 61B. The current *viâ* the X-ray tube passes through a suitable milliamperemeter M, having a long pointer N. This is connected by a long, light, insulating glass rod pivoted at P, having a contact G and moving in opposition to a spring control as shown. When the current *viâ* the tube falls below a given

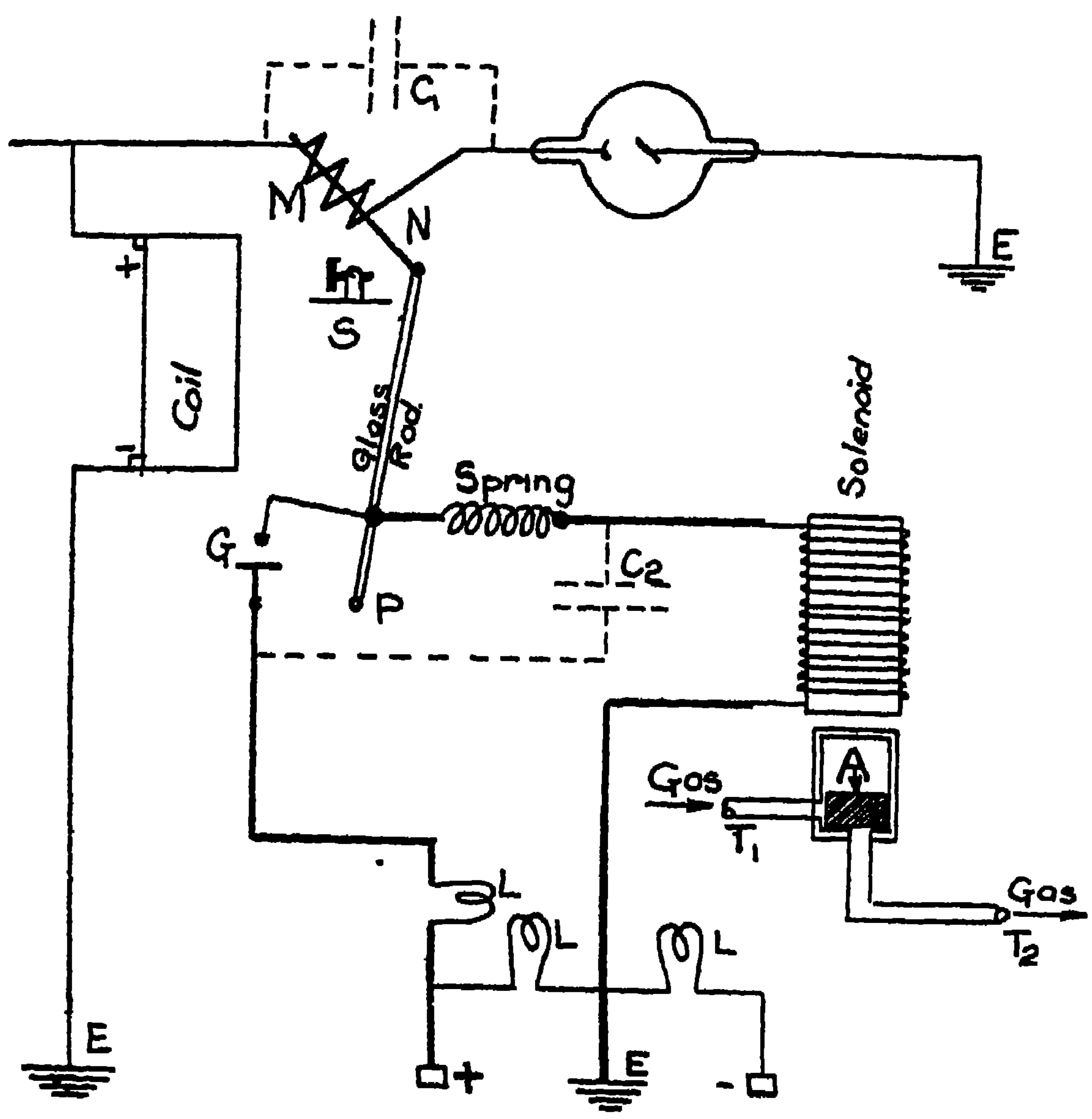



FIG. 61A.—Connections of Wintz "Automat" Regulator.

value, which can be regulated to desire by the setting of a screw S, the needle of the milliamperemeter actuates the connected glass rod and its contacts G to complete the circuit *viâ* the electrical mains to a solenoid. The core of this solenoid then attracts the armature A, in the gas circuit *viâ* $T_1$ and $T_2$, and so supplies gas to the osmosis regulator ignited by a by-pass, which causes the tube to soften.

As soon as this occurs the current *viâ* the X-ray tube increases and the pointer of the meter M moves away from the contact S and opens the gap G, so interrupting the solenoid circuit and causing the cessation of gas supply to the softening device. To avoid sparking at the contacts G and within the milliamperemeter, condensers $C_1$ and $C_2$ are inserted and lamps L, which serve as a "high-frequency device" (see Vol. I.) to

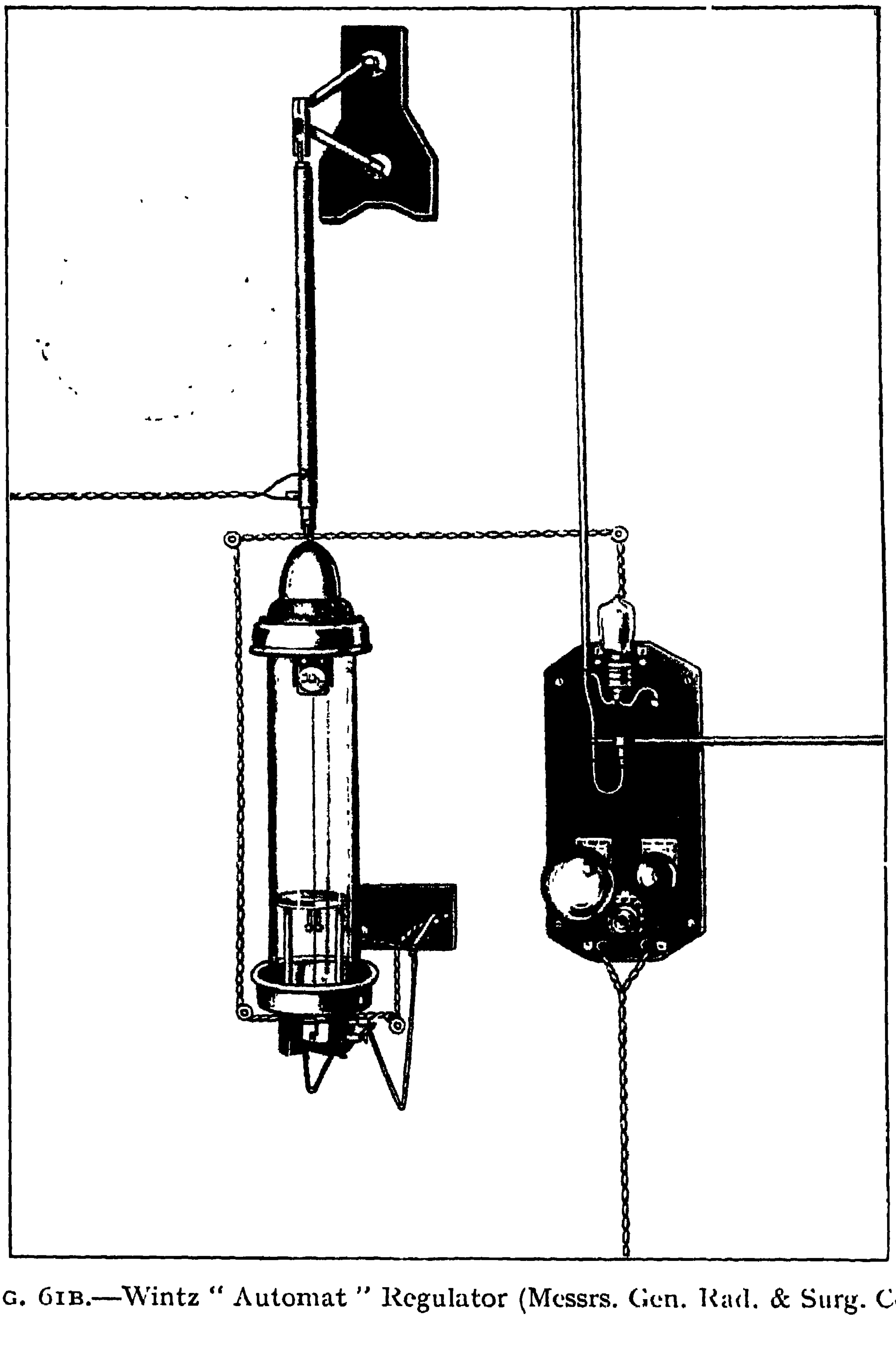


FIG. 61B.—Wintz " Automat " Regulator (Messrs. Gen. Rad. & Surg. Co.).

[To face p. 81

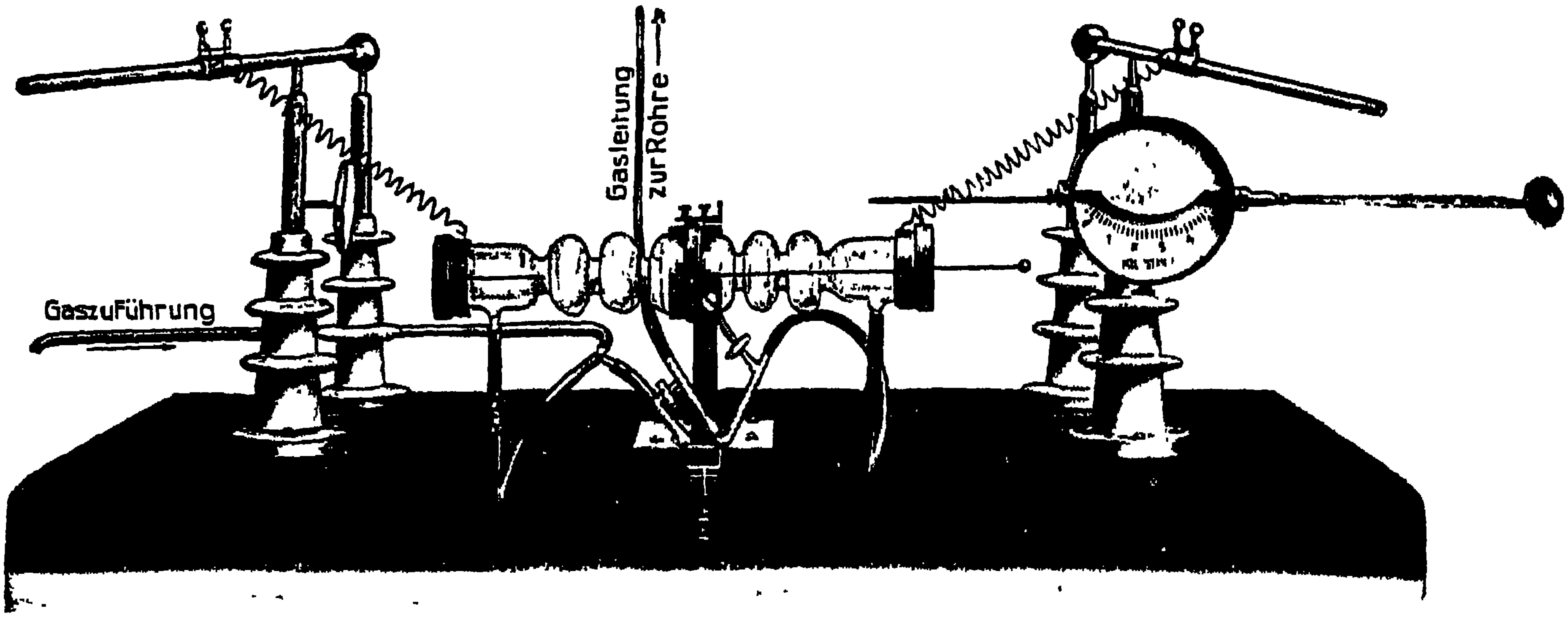



FIG. 62.—Schreuss Automatic Regulator (Messrs. Gen. Rad. & Surg. Co.).

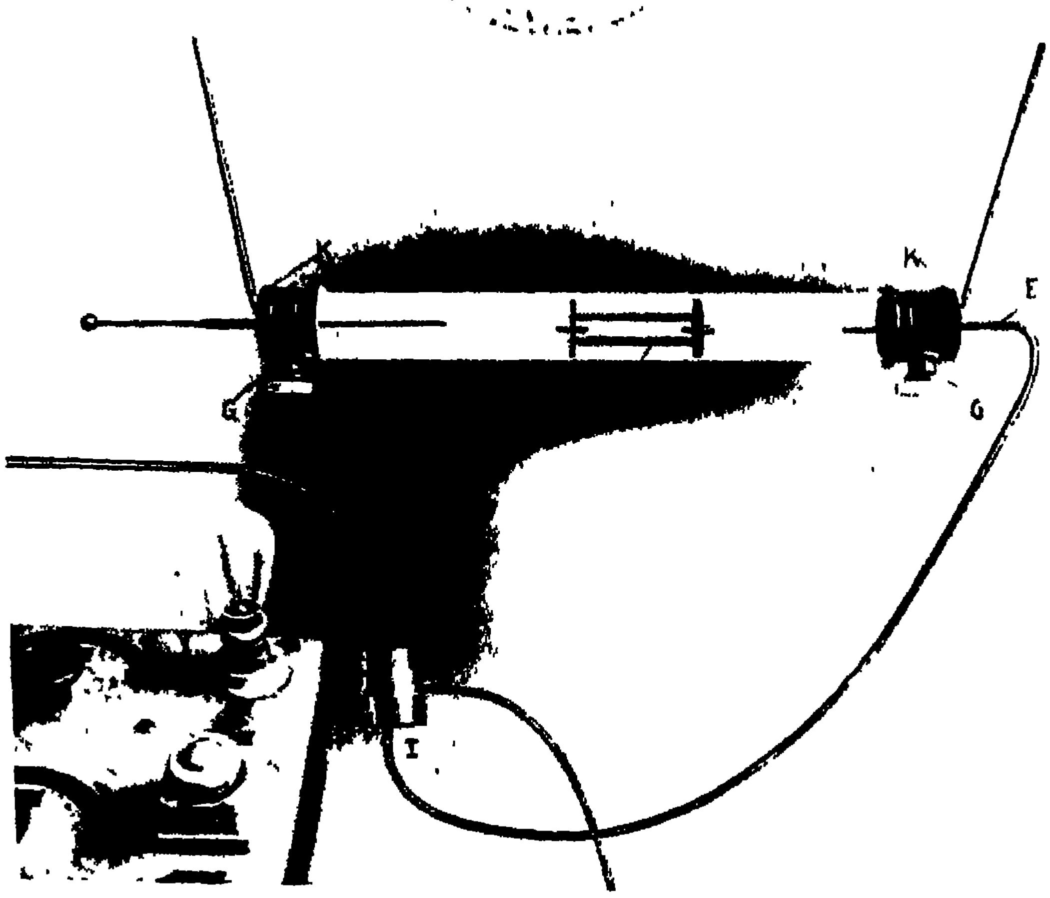


FIG. 63.—Schreuss Regulator (Müller.)

*To face p.* 85.]

provide protection against any high-frequency surges due to the heavy power induction coil operating the X-ray tube.

The milliamperemeter can be seen to the left in Fig. 61B with the glass insulation in the long vertical glass sleeve, and to the right is the solenoid valve apparatus.

*The Schreuss regulator* differs from the foregoing regulator in that it is operated by the passage of the alternative spark, *viâ* an enclosed spark gap as soon as the hardness of the X-ray tube reaches a value sufficient to cause the passage of an alternative spark.

This gap (Fig. 63) is enclosed in a glass container which not only serves to maintain the regularity of the sparking conditions but also to deaden the noise of the discharge. To maintain further the conditions of sparking, calcium chloride is placed in the vessel G to keep the atmosphere dry and to absorb nitric oxides, which would disturb the composition of the gas and tarnish the electrodes and so vary the sparking potentials. From time to time the metal parts require to be cleansed by turpentine.

The spark distance is controlled by a movable electrode and is roughly about one-third less than that of an open gap, as sparking is more easily induced by an intermediate metallic electrode T.

When the tube hardens the resulting spark causes the air within the gap to expand, and this expansion causes pressure along a rubber tube E, leading to a membrane of a valve fixed upon the control table and so causing its movement.

This movement is in turn caused to operate a valve in the gas supply *viâ* X and Y to an osmosis by-pass and so to soften the tube. When the tube has sufficiently softened the spark discharge ceases and the air in the gap contracts, so stopping the action of the valve and the gas supply. The disadvantage of this type of relay is that there is a distinct lag between the inception of sparking and the operation of the valve, due to the small but noticeable time necessary for the heating of the gas and its expansion, and a corresponding lag after the discharge ceases, necessitated by the time required for the gas of the spark gap to lose its heat and contract. Further, after long-continued sparking, the resultant nitric oxides cause variations in the voltage necessary for spark discharge and the tube has to be opened and ventilated. The supply of gas to the osmosis device may be regulated to any desired extent by rotation of the lid of the membrane valve case in order to give a slow or quick softening reaction, according to the peculiarities of the tube.

It has often been proposed to regulate the degree of hardness of an X-ray tube by direct connection to an evacuating pump. For medical radiology this has difficulties, owing to the necessity of connecting the moving X-ray tube to the fixed pump, and these connections introduce leakage and other difficulties of exhaust (*q.v.*). For physical purposes,

where a moving X-ray tube is not so necessary, it is comparatively easy to keep the X-ray tube, and particularly a metal X-ray tube, directly in connection with the pump. Many such tube-and-pump combinations have been produced with automatic pump operation.

One form of such automatic regulation is that of Küstner * designed for use with metallic tubes, where large quantities of gas may be rapidly evolved from the metal walls, so rendering the tube soft.

A suitable milliamperemeter (Fig. 64A), having a pointer Z, is connected *viâ* a choke coil D from one pole of the induction coil T to earth. On the scale of the milliamperemeter is a metallic stop I (Fig. 64B) above which a small light hammer H is poised and, by means of an eccentric cam S, is caused to make intermittent strokes. If therefore the pointer Z moves between H and I, at the next stroke of the hammer, Z is pressed

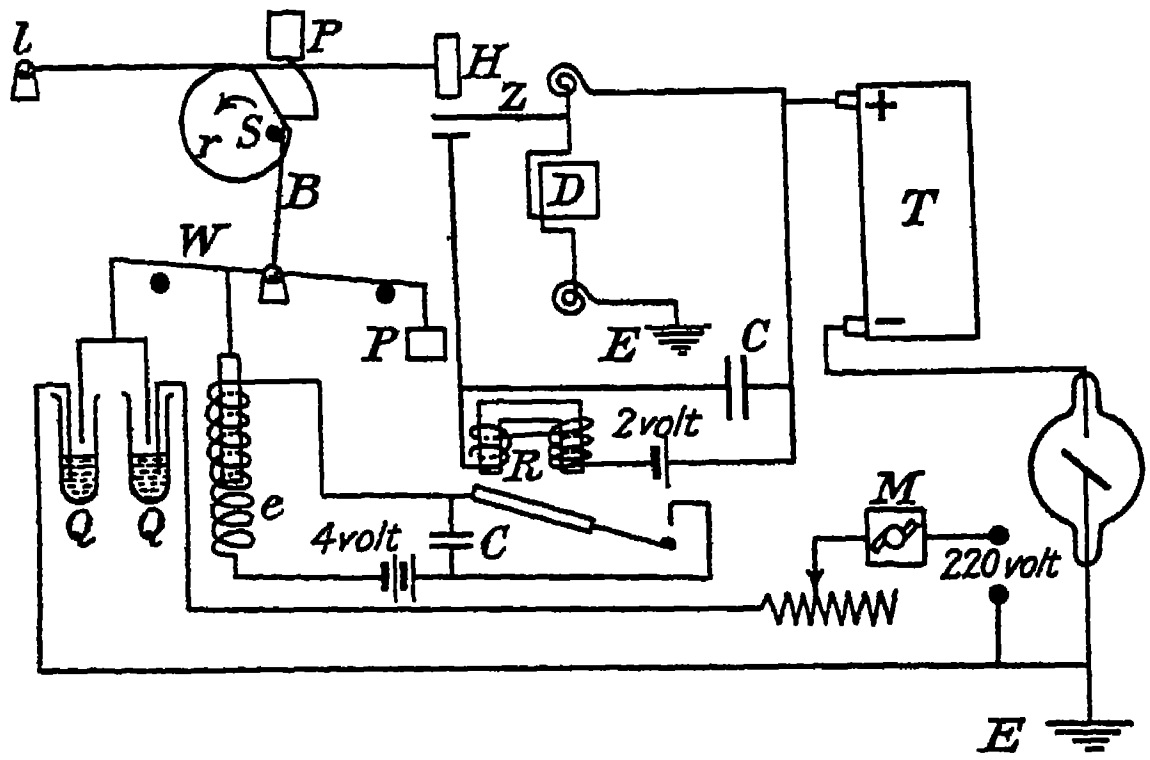



FIG. 64A.—Küstner Automatic Softening Device.

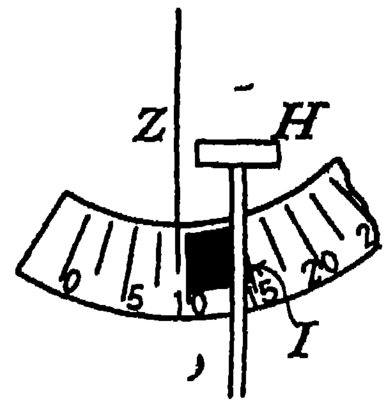



FIG. 64B.

down upon I. This closes a circuit *viâ* Z, I and a solenoid R, which in turn attracts an armature of a heavier current circuit with a solenoid *e*.

This solenoid in turn disturbs the balance of a scale W weighted by P and, when this is disturbed, its contacts enter mercury-alcohol cups Q, so completing a further circuit containing a motor M, operating the vacuum pump.

Whilst the motor of the pump is operating, the eccentric *r* geared to the motor causes intermittent pressure upon the hammer H and also interruption of the circuit of the pump motor. If the tube is sufficiently softened the milliamperemeter pointer tends, between the intermittent strokes of H, to move away from above the contact I, and has sufficient time between strokes to do so, in which case the various relay circuits are no longer closed and the motor of the pump ceases to operate.

The complication of the circuits is rendered necessary owing to the difficulty of satisfactorily closing relay circuits by the necessarily light

* *Zeit. f. tech. Phy.*, 3, 9, p. 274, 1922.

pointer of the galvanometer. In order to do this the hammer device (used in many instruments by Siemens and Halske) is utilised to make firm non-sparking relay circuit contacts.

## THE CATHODE

*Form of the Cathode.*—The emission of electrons from the cathode surface is perpendicular to the surface. If this is given a concave form (or better a parabolic form) the result will be to concentrate the electrons in the region of optical focus. The focus of the electron beam and of a light beam however differ in that the electrons are not brought to a definite focus, but take the form of Fig. 65, since as the electrons approach each

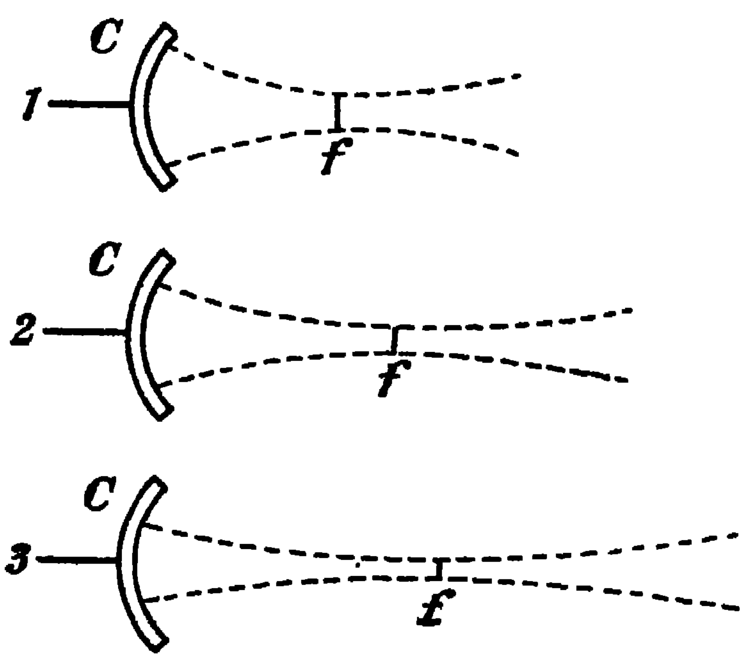



FIG. 65. (1) Soft. (2) Medium. (3) Hard.

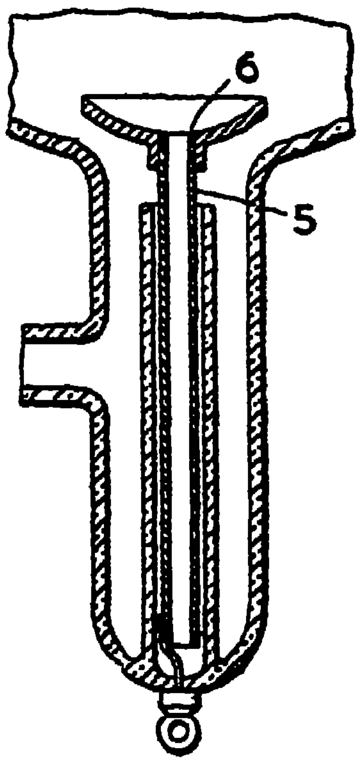



FIG. 66.—Green Cathode.

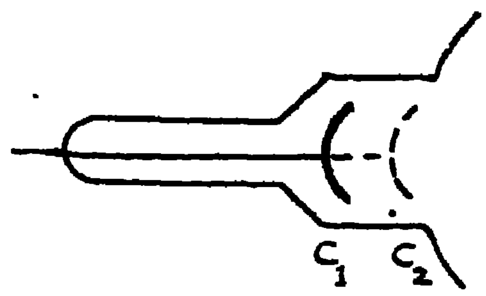



FIG. 67.

other, unlike light rays, they tend to repel mutually each other. A cross-section of the electron stream will therefore be a hollow circle, the cross-sectional area of which, and the relative position in respect to the optical focus of the focus *f*, will be dependent upon the potential applied to give rise to the electron beam.* If this increases, the kinetic energies of the electrons become greater and they tend to approach more nearly to the optical axis (Fig. 65 (2) and (3) ) before their mutual repulsions become effective, *i.e.*, the electron stream is more sharply focussed and the focus tends to move away from the cathode.

The focus of the cathode is also dependent upon the gaseous pressure. If this is comparatively great, the electrons tend to lose their energy, by collisions with gas atoms, before they reach the focus, and the effect is the same as if the tube were operated at a lower potential. In these respects the electronic focus differs from the light focus. The " focus " of the X-ray tube itself will vary as to whether the target of the tube

* Campbell Swinton, *Nature*, 55, p. 568, 1897.

is situated actually at the optical focus of the cathode or not, as well as upon the applied potential.

In practice, although the tube's focus is more fine if the target is situated at the optical focus of the cathode, the target is arranged so as to be defocussed slightly with regard to the electron beam. The reason for this is that the electronic impacts upon the target give rise to considerable heat by the conversion of their kinetic energy to heat energy. If the electron stream is too sharply focussed there is extreme concentration of the heat and, as a result, fusion and pitting of the target is very likely to occur. A less sharply focussed tube of much longer life is therefore usually preferred.

In order to produce a defocussed and parallel beam Green (Brit. Patent 23,316/1909) uses a cathode (Fig. 66) with a hollow centre supported upon a tube, so that the centre of the cathode is absent and does not give rise to the most highly focussed cathode rays. Alternatively the centre of the cathode is covered by a glass head to prevent emission from this region.

The form of the cathode beam can be much altered by means of shields, and is also varied in relation to its relative position in the cathode sleeve.* If the cathode is withdrawn into the tube as from $c_2$ and $c_1$ in Fig. 67, the electrostatic flux and electron paths are, by the electrostatic action of the glass sleeve, concentrated towards the cathode centre. To overcome the mutual repulsions of these more compactly distributed electrons, greater energy, *i.e.*, potential, is required and the tube appears to be "hard." Conversely if the cathode is placed away from the cathode neck and towards the centre of the bulb the tube appears to be "soft." In such a case the electrons are more apt to be emitted in all directions rather than to be concentrated in the axis from cathode to target. Such is not the case in the electron tube, where the cathode is towards the bulb centre, but in which it is usual to aid the concentration of the electron stream by the use of shields or hoods.

Regarded from the aspect of potential fall there is, when the cathode is in the bulb, an infinite number of approximately equal resistance paths of electrostatic flux between cathode and anode. When however the cathode is within the cathode sleeve the less direct and highly resistance flux paths are *viâ* the glass sleeve of high specific inductive capacity, and the low resistant paths, which the electrons tend to follow, are directly between cathode and anode.

Serving to concentrate the electron stream is also the fact that electrons emitted from the cathode pass to the glass in the region of the cathode neck and give this a high negative charge. This charge reaches such a value that it tends to repulse the emission of any further electrons of similar charge in this direction and the applied energy is more usefully

* This subject is also discussed by E. Heermant and R. Thaller, *Zeits. für Phys.*, 29, p. 130 (1926).

utilised in causing the passage of electrons more normal to the inner concave cathode surface. This effect will be the more, the more the cathode is made to enter the cathode sleeve. Such a fact has been well known since the early days of X-radiation technique and was first described by Campbell Swinton,* who fully realised the necessity of fixing the cathode in relation to the cathode neck, according to the work for which the tube was intended.

Swinton used tubes in which the hardness could be varied by means of the position of a glass s'eeve *s* (Fig. 68) sliding along the cathode, the effect of which was to still further increase the emission of electrons directly between cathode and anode for the reasons already given. Later Reynolds (Brit. Patent 15,193/1900) attached to such a sleeve eccentrically arranged weights *d* (Fig. 69), which allowed the position of the glass

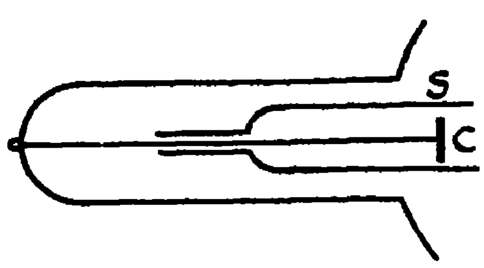



FIG. 68.—Swinton Sliding Cathode Sleeve.

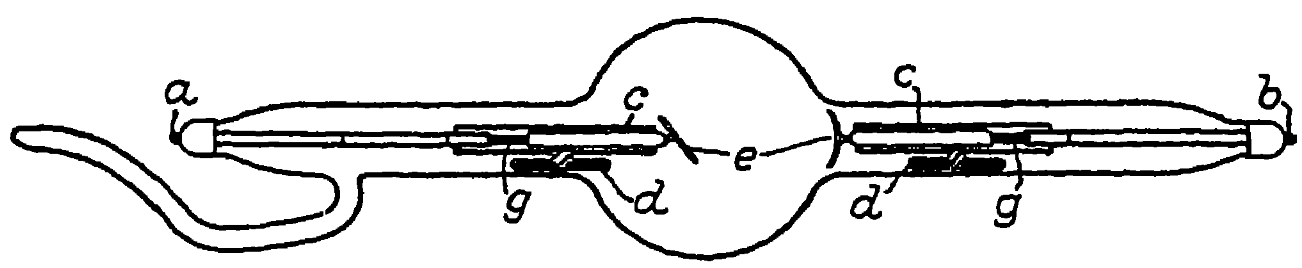



FIG. 69.—Reynold Tube.

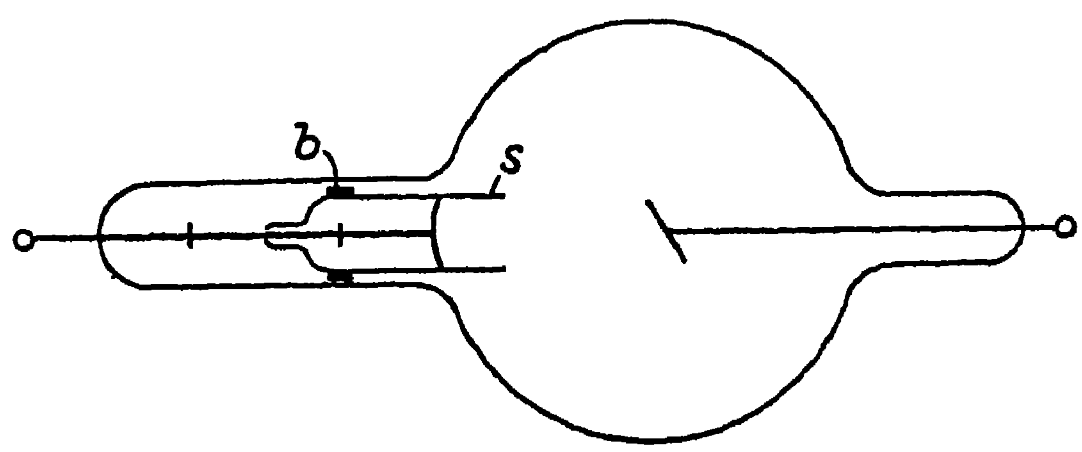



FIG. 70.—Whiddington Tube.

sleeve *c* to be moved along the cathode stem by rotating the tube whilst the eccentric weights held the surrounding glass sleeve fixed in space. Laurey (Brit. Patent 14,004/1910) and Whiddington (Brit. Patent 1,292/1911) varied the position of such a cathode sleeve by attaching to it a magnetic mass *b* (Fig. 70), capable of movement by means of an external magnet.

In order to diminish the concentration of stress upon the glass in the region of the cathode, various methods, have been adopted and the method of Winter (Brit. Patent 39,143/1909) should be particularly mentioned (see p. 67).

Connection to the exterior of the tube from the cathode (and other) electrodes is commonly made by means of a platinum wire. To prevent fracture of this wire, abruptly held by the glass, it is surrounded by a cathode cap which securely fixes the position of the wire and so avoids

* *Nature*, 55, p. 621, 1897.

bending and at the same time allows the fixing of a ring to the wire to act as a convenient connection. Such a cap is fixed by a suitable cement.

*Sputtering of the Cathode.**—When energy passes *viâ* an ionic gas tube there is a passage of negative electrons of small mass and high velocities from cathode to anode and a converse passage of positive ions, derived from the gas, of comparatively high mass and low velocities.

These ions pass to the cathode, which arrests their motion, and their kinetic energy is transformed to heat energy. In addition to the kinetic-to-heat energy transformation, mechanical effects occur by which masses above atomic dimensions are mechanically separated from the cathode. The cathode is therefore disintegrated or "sputtered." The freed super-atomic masses, having a negative charge, are drawn to the positively charged tube walls, to which they adhere. Being in a finely divided condition they possess a large surface upon which considerable quantities of gas are adsorbed by occlusion. Gas is in consequence removed from the tube atmosphere and the vacuum further lowered, *i.e.*, the tube "hardens," a greater applied potential being necessary in order to pass a current equal to the original current.

The sputtering of metals by bombardment was first studied by Crookes, prior to the discovery of X-radiation, *i.e.*, in 1891.

Crookes found the sputtering to occur roughly in proportion to the atomic weight of the cathode element, being greatest for the heavy metals, as palladium, and least for light metals, as aluminium. Their relative sputtering, taking that of palladium as 100, was found to be ;—Pd, 100 ; Au, 92 ; Ag, 76 ; Pb, 69 ; Sn, 52 ; Zn + Cu, 47 ; Pt, 40 ; Ca, 37 ; Cd, 31 ; Ni, 10 ; Ir, 10 ; Fe, 5 ; Al, 0 ; Mg, 0.

The sputtering does not however depend only on atomic weight and varies with ;

(1) The temperature of the cathode, becoming greater as the current *viâ* the tube (and resultant temperature) is increased.

(2) The nature of the surrounding gas, being least for common gases, such as H, N and $CO_2$, and greatest for the inert rare gases, He, A, Ne and Kr.

(3) The current *viâ* the tube.

(4) The fall of potential in the neighbourhood of the cathode, which we now know determines the velocity and kinetic energy of the bombarding ions.

(5) The pressure of the gas, the sputtering increasing as the pressure is lowered. This is doubtless due to the fact that an ion is less likely to undergo collision with gas molecules as the pressure is reduced and therefore acquires and retains a higher velocity and kinetic energy and, as a result, on impact with the cathode, greater energy and greater heat development is involved.

* The question of sputtering has recently been newly treated by A. Güntherschultze, *Zeit. f. tech. phy.*, 8, p. 169 (1927).

From the classical Crookes experiments it follows that to diminish sputtering and resulting irregularity of cathode surface and focus, this electrode should be formed of a light element, as aluminium, calcium or magnesium. Theoretically a cathode of glucinium (atomic number 4) would be better than aluminium (atomic number 13) particularly as the former metal does not fuse until at 1,200° C. The comparative rarity and resulting cost does not however allow its common use.* On the score of such expense, of the other three metals, aluminium is the most practical when considerations of facility of working are also considered. Pure aluminium is however inferior to commercial aluminium containing sodium † as an impurity.

Coolidge has tried tungsten, but found it very difficult to obtain a discharge *viâ* a gas tube with this metal.

The use of a metal of low atomic weight as cathode, appears to be dependent upon the weak attraction of the low-valued atomic positive nucleus for the negative atomic electrons, which are, in consequence, easily expelled from the atom to take part in current passage. Such emission of electrons has been attributed to a purely localised heat effect due to the arrest of the positive gas ion and consequent energy transformation.

Villard‡ has shown that the emission of electrons by the cathode is a discontinuous and not a continuous effect, when the electron beam is analysed from a rotating cathode. The rate of emission varies from 2,500 to 5,000 per second. This result has been interpreted by Perkins§ in terms of electrical oscillation of the tube circuit.

Since the electron emission from a heated filament is a continuous effect, this would indicate the greater suitability of the electron tube, as compared to the ionic tube, for very rapid repeated exposures as in X-radiation cinematography.

A cathode of a gas tube after a little use always shows an iridescent ring within its cup, the colour of which varies with the thickness of the deposit, owing to interference effects. This coloration is due to purely chemical action and not sputtering, for example, the formation of a film of oxide, or nitride, with the gas of the tube atmosphere.

In spite of many statements to the contrary the sputtering effect is very noticeable indeed in electron tubes which have had considerable wear and the deposited film gives rise to colour effects. One would expect, since a heavy metal as tungsten is generally used as the cathode in an electron tube, that combined with the large free mean paths of any residual ions the effect would be most pronounced, as is the case. Unlike the gas tube, such sputtering cannot have any bad effect, as in the

* Recently this metal has been used by Siemens and Halske for another purpose (see p. 111).

† R. V. Hirsh and F. Soddy, *Phil. Mag.*, 14, p. 778, 1907.

‡ "Les Rayons Cathodiques," p. 71.

§ *Comptes Rendus*, p. 1389, 1909.

ionic tube, since its occlusion powers only renders the tube more perfectly exhausted.

Very often in well-used electron tubes a ring will be found upon the glass bulb which is the projection of the circular cathode shield. One favourite spot for such sputtering is in the region of the cathode neck, where the variation of potential is intense and to which any residual gas atoms appear to be drawn and to give rise to sputtering, a very intense dark ring being often found in this region.

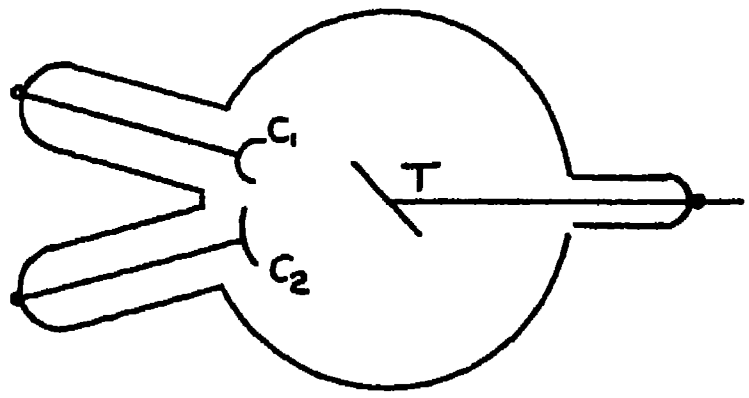


FIG. 71.—Bi-cathode Tube.

The cathode of the gas tube is supported upon a sleeve of the same metal, *i.e.*, aluminium. To fix this to the platinum wire giving external connection, the cathode sleeve is usually surrounded by a re-entrant glass sleeve and the cathode is prevented from sliding or rotation by passing a wire through suitable holes in both the metal and glass sleeve.

*Bi-cathode Tubes.*—From time to time tubes have been produced with two cathodes.

One object of such bi-cathode tubes (Fig. 71) is to give two variations of focus. With one cathode $C_1$ the cathode beam is sharply focussed upon the target in order to give sharp radiographic definition for short exposures

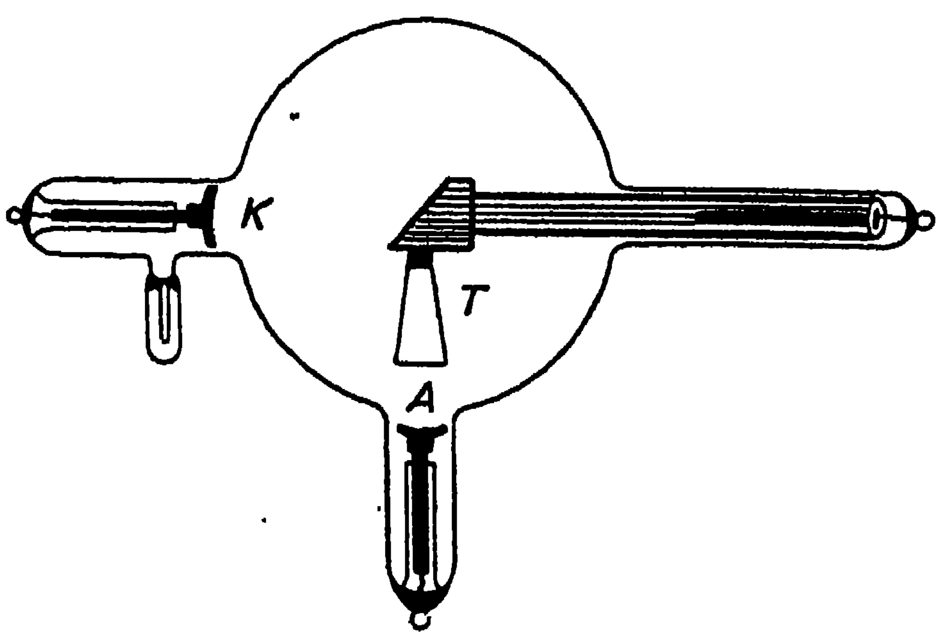


FIG. 72.—Bi-cathode Tube (Koch and Sterzel).

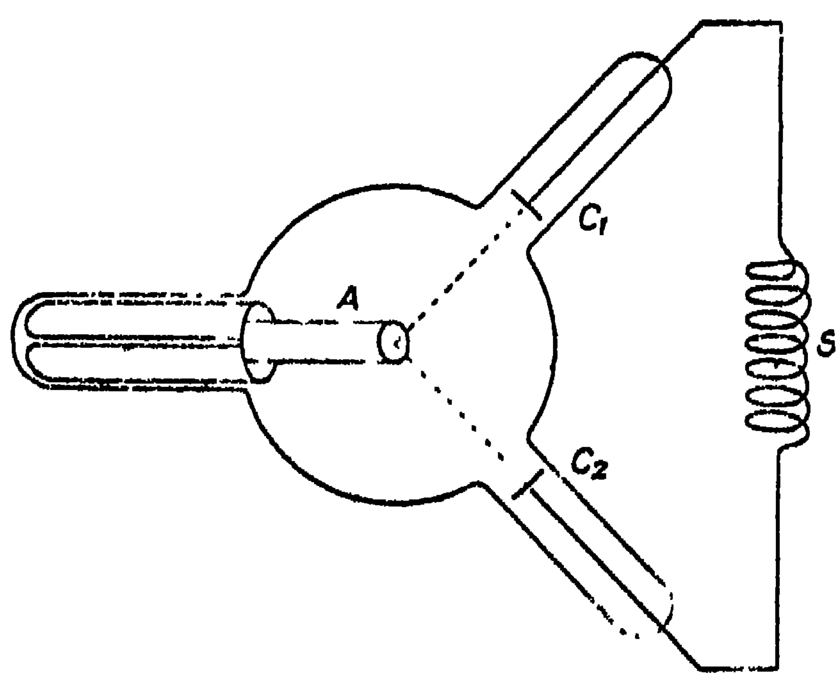


FIG. 73.—Wertheim's Tube.

the other cathode $C_2$ having a broad focus for long-continued radioscopic work when, with a sharp focus, the target would be overheated and pitted.

Messrs. Phönix have used such double cathodes both in the ionic and the electronic types of tube (p. 154).

The other object of bi-cathode tubes is to arrange for inverse current to pass to a second cathode, so arranged that the resulting X-radiation is thrown in a different direction to the main X-ray beam and cannot, in consequence, cause photographic blurring.

This has been used by Koch and Sterzel * and is essentially a combination of an X-ray tube and valve tube (Fig. 72). When used with an induction coil the inverse current passes from T to A and is so by-passed from the direction of emission of the useful target surface. Wertheim utilised a bi-cathode tube (Fig. 73) with an entirely insulated anode A in which an alternating current source sent energy from "cathode" to "cathode" and the cathode stream from either cathode was directed upon the symmetrically arranged insulated target of A. Such a tube allowed the direct application of alternating current to the tube, but its use has not become general. The more extended use of rectified alternating current, in place of the induction coil discharge, has resulted in the decline in the use of valve-tube and X-ray tube combinations. In the case of the double-focus bi-cathode tube, the use of either cathode involves a high-tension change-over switch operation, during which a patient, carefully posed by radioscopy, may move before the change-over can be made and a radiograph taken. In the electron tube this difficulty can be avoided (see the "Autofok Tube," p. 190).

Furstenau and others have produced bi-cathode and bi-anode tubes for stereoscopic purposes (*q.v.* p. 421).

*Cooling of the Cathode.*—In use, during long-continued treatment, the cathode may develop a high temperature. As a consequence increased sputtering or even fusion of the cathode may result, unless this electrode is cooled by one of the methods more conveniently considered under the section upon the anticathode.

## THE ACCESSORY ANODE

The action of this supernumerary electrode, which like the cathode, is made of aluminium, is very obscure. Kaye states "the precise benefit of the anode is a little doubtful, though in some cases the result of disconnecting it from the anticathode is to soften the tube."

Most writers evade any close discussion as to the precise object and mode of action of this electrode, merely contenting themselves with the view that it has a "steadying action" on the operation of the tube, without explaining how such action can arise.

In order to clear up this point, the present author has sought information from all the chief English and German tube makers, including Herr Emil Gundelach, who was responsible for the introduction of this accessory electrode in 1897.

If we examine the position of this electrode, in a number of tubes, it will be found it is always placed in one of two positions, namely :—

(1) Directly behind the anticathode, so that the anticathode is approximately equidistant from cathode and anode, as shown in Fig. 74.

* Brit. Patent 14,196/1904.

(2) Behind the anticathode with its axis inclined to the cathode-anticathode axis, as shown in Fig. 75.

The author advances the following view as to the action of this electrode.

Considering the first case (Fig. 74), if the anode were absent there will be a fall of potential between the target and the cathode, but not necessarily a gradual potential fall, it being well-known there is an abrupt fall in the region of the cathode.

An electron, leaving the cathode, would, by virtue of this field of potential, at first acquire velocity to reach its maximum velocity at some point between cathode and target but, as the target is approached, this velocity will tend to decrease, since the electrons converging towards the target will mutually repulse each other and so decrease mutually their velocities.

By the Einstein-Planck relation $\frac{1}{2}mv^2 = Ve = h\nu$, the quality of

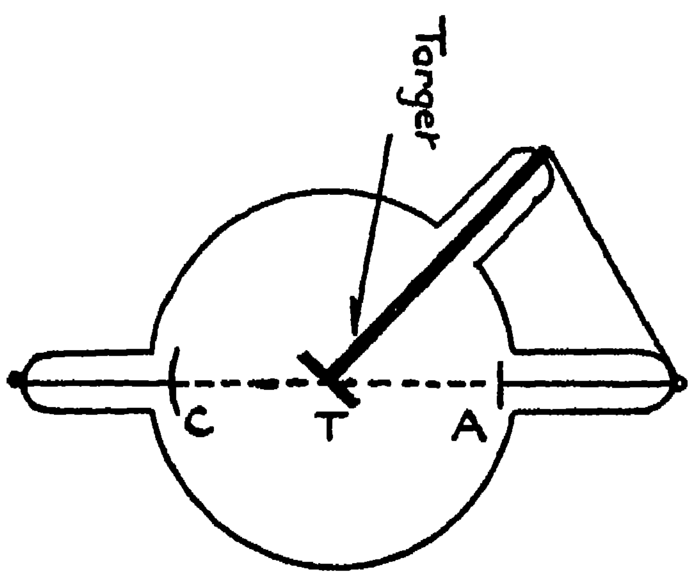



FIG. 74.

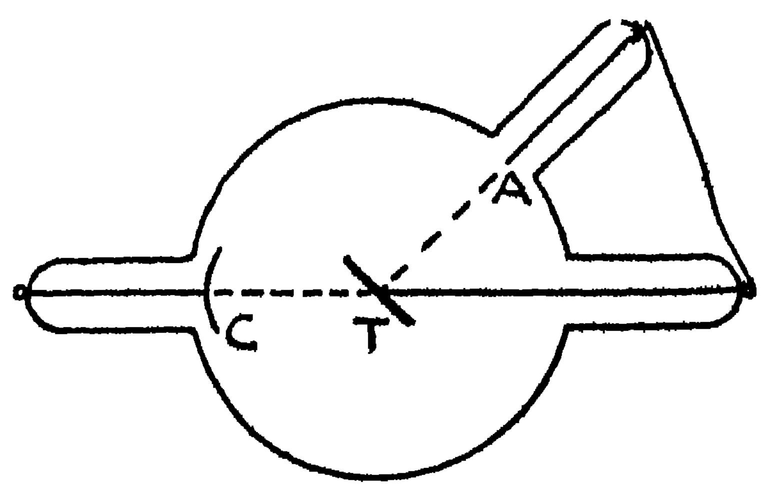



FIG. 75.

radiation, or hardness, is dependent upon the electronic velocity and any decrease of this must cause a decrease in the quality of radiation, as compared to the quality if impact were to occur at that portion of the electronic path where the velocity is at its maximun value.

If now the anode is inserted behind the anticathode, as shown, the potential fall is no longer between cathode and target, but between cathode and anode. The anticathode is generally at a higher potential than the anode and must necessarily be so since there is a current flowing *viâ* the connecting wire between anticathode and anode. The result is that electrons passing from the the region of highest negative potential at the cathode, accelerate to their maximal velocities and then decrease their velocities as they approach the anode. The target is however situated in the region of maximum velocity and, in consequence, the quality of radiation emitted from it is improved.

This view takes no particular notice of the intensity of radiation, but only of quality of radiation. Whereas the quality of radiation may be more spectroscopically "soft" when the third electrode is removed,

actually since one electrode is now no longer functioning, the current *viâ* the tube may be less, *i.e.*, considered from current-carrying aspects, rather than spectroscopic aspects, the tube is " hard."

An alternative view is to regard the action from a " space-charge " view in which the action of the anode is to attract and remove the electrons in the tube atmosphere and by such removal reduce the number of electrons per unit volume and so to reduce the repulsive and retarding effect of the space charge to electrons leaving the cathode during their passage to the target, so increasing their velocities.

It is further not known how much part this electrode plays in removing the positive charge of the wall, particularly since at high voltages such glass is partly conductive. Since, according to Dauvillier, the electrons necessary for conduction are largely produced by ionic impact upon the walls, a high positive charge upon the walls will tend to repulse such ions and thereby reduce the electron supply.

This will prevent discharge until some of this wall charge leaks away, to allow further ions to bombard the walls. If we could therefore visualise this effect we should see a " flickering " of the tube during this process, which Villard has shown definitely to occur. By allowing the charge to partially escape from the walls this effect is greatly reduced.

The action in the second arrangement (Fig. 75) is the same, as far as the relative positions of the electrodes are concerned, with a further action. Since the path between cathode and anode is now a curved path, as shown approximately by the dotted lines of the figure, the electrons following this path tend to strike the target face perpendicularly rather than at an angle, as would be the case were the anode absent. There can be little doubt that such an impact, normal to the target surface, must result in the electrons being more directly and quickly brought to rest with increased radiation of energy. In the case of an inclined impact there is greater possibility of the electron being only reflected at the surface with reduced velocity, and therefore all its energy is not given up as radiation. The question of such " recoil electrons " has been specifically studied and with such recoil, the radiation energy emission must be less than when recoil does not occur.

Having considered the theoretical aspects of this question we will now consider the practical results, as advanced by various tube manufacturers, the first opinion being that of Herr Gundelach, originally responsible for the introduction of the electrode.

(1) *Herr Emil Gundelach.*—" The accessory anode, as you correctly remark, was first introduced by myself to prevent the sputtering of the anticathode during evacuation.

" At the time all X-ray apparatus had inverse current. If therefore only cathode and anticathode were present naturally much sputtering occurred, when this acted as cathode for the inverse current.

"It is well known that the metal of the anticathode sputters and coats the glass wall. Aluminium forms a single exception.

"In order to prevent the sputtering of the anticathode, a second anode was introduced. The high potential current which during the evacuation of the tube must be passed in order to 'gas' the metal, was now applied to the cathode and second anode. Thereby the sputtering of the anticathode metal was completely prevented. The anticathode was only used for a short time, towards the end of the evacuation, with a weak current.

"Nowadays, we also have tubes for evacuation, which have only a cathode and anticathode, since sputtering does not occur since we possess (transformer) apparatus which works without inverse current.

"In actuality many ionic tubes are delivered with only two electrodes. Most tubes have however still the second anode, since by the simultaneous use of two anodes (anticathode and accessory anode) a more regular steady discharge is produced."

(2) *Cuthbert Andrews, Esq.*—"From a strictly practical point of view you would be safe in assuming that the chief function of the auxiliary anode is to render assistance to the manufacturer during the exhaustion of the X-ray tube. For various reasons the provision of this armature is of considerable convenience, and it is mainly the use which is made of the anode during exhaustion which justifies the statement it has a 'steadying' effect upon the tube. Apart from this however, it is quite sure that the same steadying effect does obtain after the tube is finished and in use. We have made various types of tube without an anode at all, and although one can get quite a good working tube, it is never quite the same as the bi-anodal type.

"There is probably little doubt that your first assumption is mainly correct. That is to say that the velocity of the electrons is increased when the anode is present, and it seems likely that this would result in the effect of inverse current when passing being minimised, so that the destructive effect of such inverse current is greatly delayed."

*Messrs. Cossor, Ltd.*—"As regards the secondary anode in the X-ray tube, the object of its introduction is to localise in the immediate vicinity any surplus gas which may be present in the tube. Without this third electrode, such free gas particles accumulate in the neighbourhood of the anticathode, and in view of the charge sustained by such a nebula of gas the cathode stream is deflected as such a charge accumulates and disperses with the result that the tube works erratically.

"Upon the introduction of the third electrode, the gas accumulates in the immediate neighbourhood of this electrode and does not so materially influence the cathode stream, with the result that the tube is far more steady in its operation."

*Messrs. C. H. F. Müller.*—"The special anode in the gas tube was, before all other considerations, necessary to evacuate the tube, since most anticathodes, consisting of platinum or copper, are strongly sputtered when they have a negative potential. Formerly we were compelled to excite the high tension for X-ray tubes by means of induction coils, which, as well as the useful voltage, gave oppositely directioned voltage, and at this time the valve tubes used were not so effective in reducing completely this fault of voltage. During evacuation it was therefore possible to connect the induction coil without sputtering of the anticathode occurring. In consequence the positive pole of the induction coil was connected to the anode and the anticathode not put in circuit.

"Meanwhile we have found the ways and means to suppress this wrongly directioned destructive current, for example, by the application of hot filament

valves, and we therefore no longer use the accessory anode on the pump. We therefore only still insert the accessory anode in ionic tubes when this will favourably influence the operation of the finished tube. A tube with an anode combined with the anticathode is always softer than the same tube when the anode is cut out and the positive high-tension connection is applied directly to the anticathode. If we connect the high-tension lead only to the anode and leave the anticathode free, then the tube is still more soft. It is evident we cannot employ this latter connection. Your view upon the accessory anode is therefore correct."

*R. S. Wright, Esq.*—" The ' steadying action ' of the bi-anode is probably due to the fact that this electrode provides a second source of positive ions. The discharge through the tube depends on the bombardment of the cathode, as you are well aware. The beginning of the discharge will be determined by the freedom with which positive ions are produced. In the initial condition of the tube, before the discharge begins, but while the potential difference across the tube is rising, positive ions are produced most freely, if not entirely in the neighbourhood of the positive electrodes. The provision of a second positive electrode (the bi-anode) in addition to the target, gives a second possible source of positive ions and facilitates the setting-in of the conditions necessary for the discharge to begin.

" The effect of the bi-anode, in this respect, may be smaller or larger than that of the target, depending on the dimensions, position, surface condition, and probably also on other conditions of the two positive electrodes. It is well known that some tubes work ' softer ' on the bi-anode than on the target alone, and that the reverse is found in other tubes, but in practically any tube the steadiest condition of working is obtained when both the positive electrodes are used."

*Messrs. Phönix X-ray Tube Company.*—" Regarding the mode of action of the third electrode in the ionic tube we state the following ;—

" It is known that with greater electrode distances a gas discharge occurs more easily than with a small distance. The Hittorf alternative spark experiment shows this effect very obviously.* When we consider that an electron can easily ionise a gas molecule when its ' free mean path ' is smaller than the electrode distance, then this effect is self-evident.

" If now the third electrode, the so-called anode, is, in an ionic tube, further distant from the cathode than is the anticathode, then ionisation will occur more easily over the discharge path between cathode and anode, than between cathode and anticathode. The discharge is then directed between cathode and anode.

" If the induced and greater quantity of ions and electrons have been excited in the discharge space then, in consequence of the powerful ionisation now present, it is possible for breakdown to occur between the former unfavourable path between cathode and anticathode. This path is now the most important as it is shorter and therefore the field strength is greater, whilst the auxiliary discharge has formed so many electrical carriers (ions and electrons) that there is sufficient ionisation present to maintain this discharge.

" The third electrode therefore serves to ' ignite ' the discharge. It is this action which is intended when most authors state the discharge is made more regular

* In this experiment it is shown that an electrical discharge will pass more easily *viâ* a long spiralar gas path than directly between a pair of electrodes, so closely approximated that, at the particular gas pressure, an electron is unable to acquire the necessary ionising velocity during its passage between the electrodes.—AUTHOR.

"Particularly when, as with ionic X-ray tubes, for induction coil work, the anticathode stem is surrounded by a glass cylinder, is this third electrode necessary. Discharges over a longer path, namely between anticathode stem and cathode are in these tubes suppressed by the glass mantle being in the way. The shock of discharge must then take place between anode and cathode. The glass cylinder upon the anticathode stem has, as is well known, the object of suppressing and making non-active the inverse current, *i.e.*, the reverse polarity voltage impulse, which occurs on the make of the primary current. By covering the metallic anticathode stem with glass this object can be obtained, as the gas discharge is then less induced, the smaller the uncovered surface of the negative electrode. Also the growth of the discharge current is hindered by the small surface of the negative electrode. The so-called 'abnormal cathodic fall' enters into question as soon as the total cathode surface is enclosed by the cathode space.

"So the third electrode does not favour the inverse current, since it has a small surface and is wisely placed in the extension of the glass bulb.

"In ionic tubes which are worked with well-rectified high-tension alternating current, *i.e.*, with transformers by the application of a rotating rectifier and not with induction coils, with more or less effective rectification by gas-filled valve tubes, it is unnecessary to enclose the anticathode stem in a glass cylinder, as inverse current can by this mode of working not occur.

"When however the whole anticathode stem is uncovered, there are other long discharge paths present between cathode and anticathode, and the inception of ionisation can therefore result. In such ionic tubes the third electrode is omitted, as it is no longer necessary.

"The third electrode can also be omitted in ionic tubes for induction coil work if we make a hole in the far end of the glass mantle of the anticathode and so make the far end of the anticathode stem unclosed. For the action of the discharge this place of the anticathode stem then acts as the third electrode.

"The action of the third electrode for completed tubes is now sufficiently explained. We must also mention that there are ionic tubes in which the presence of the third electrode is not to be explained upon the above grounds.

"In these tubes the third electrode is introduced on grounds not in connection with the discharge process. The third electrode is introduced when it is unnecessary for the discharge process, as the tubular mouthpiece of the glass bulb permits the tube to be held more firmly. As the third electrode does not destroy the discharge process, such mass productions are not to be despised, even when they are unnecessary.

"We have still to discuss the importance of the third electrode for the pumping process.

"As is well known, during electrical discharges in rarefied gases the metal of the cathode sputters. Particularly do heavy metals sputter easily. Aluminium sputters very little. On this ground the cathodes of gas tubes are made of aluminium. Since formerly we only had induction coils, in the pumping process the inverse voltage, particularly so long as considerable gas was still present in the tube, sputtered the anticathode mirror when the voltage was directly applied to the anticathode and cathode. To diminish this, the voltage was only applied to the cathode and third electrode and the anticathode remained unconnected. The anticathode was so never directly the negative electrode, but was 'gassed' by the impacting electrons. The third electrode, being of aluminium, could not be sputtered when it was, during inverse current, the negative electrode.

"These former pumping operations explain why it is that many authors

state the third electrode is necessary for the pumping process. Nowadays the third electrode is no longer used for the pumping process, since we have at our disposal rectified transformer high voltage."

From the above we see that considerable difference of opinion exists as to the precise effect of the anode during tube operation, although the use during exhaustion is generally agreed.

We may summarise these opinions regarding the function of this electrode as follows ;

(1) To allow the passage of inverse current during evacuation, without injury to the target face.

(2) To allow a similar passage of inverse current during normal operation after manufacture.

(3) To " fire " or cause the inception of ionisation and thereby render breakdown more easy and the operation more steady and regular. (Phönix Company).*

(4) To produce increased positive ions for cathode bombardment (Wright).

(5) Possibly to remove space charge during operation as well as charge upon the tube walls (Leggett). If we substitute "positive ions" for " residual gas " this concurs with the view of Messrs. Cossor.

(6) To cause, in some arrangements, direct and not glancing impact of electrons upon the target and diminution of "recoil electrons" (Leggett).

(7) To facilitate discharge, by virtue of its usually pointed form in comparison to the flat target, by the usual action of a point during discharge (Leggett).

The effect upon the tube's action by disconnection of the anode-anticathode appears to be undecided, but are generally contrary to the view often expressed that the tube is thereby softened. Difficulties arise as to the exact meaning of " softness," since whereas the radiation may be of longer wavelength and therefore soft, this does not invalidate the fact that actually less current may pass *viâ* the tube.

Wright states that a tube may be either rendered soft or hard by this disconnection of the anode.

Müller states a tube is hardened by this disconnection and Messrs. Phönix give very good physical reasons why breakdown should then be more difficult.

The author can aid this discussion by practical results. Owing to the rectifier of a transformer apparatus slipping from its true position upon the spindle shaft several gas tubes, in attempts to obtain radiographs, were overloaded with the resulting unuseful radiation and so rendered too soft for use. These tubes have however been usefully employed, with excellent results, by disconnecting the anode, so allowing a higher voltage

* The possibility of the anode causing high-frequency oscillations and more easy discharge should not be neglected (p. 187).

to be applied without the occurrence of a large unuseful current, *i.e.*, the tubes then run " hard " as measured by current.

Three of the above opinions are to the effect that this third electrode is not necessary when modern transformer excitation, free from inverse current, is being employed, and there is certainly a growing tendency to omit this electrode. To overcome this electrode's use, during evacuation, Müller has introduced in its place a heated filament, the purpose of which is to provide electrons during evacuation by acting as cathode and after this use the filament may be sputtered to give finely divided metal to absorb gas and maintain the high vacuum.

Philips omit the pointed anode but furnish a metallic circular deposit behind the anticathode target (Fig. 76) the purpose of which would appear to be to act as anode in the manner described upon p. 94. Such an accessory electrode would appear to have little action as regards suppression of inverse currents, but it is claimed that it gives a more regular action than the point anode.

In conclusion the action of this point electrode in facilitating breakdown, due to its pointed form, should be recognised in comparison to the flat anticathode. This action is entirely additional to the increase of gas-path effect (p. 97).

*Other Accessory Electrodes.*—From time to time other accessory electrodes have been introduced into gas tubes in order to regulate the discharge. These differ from the anode already discussed in that they have been situated not behind the anticathode but between cathode and anticathode. The first British X-ray tube patent, by Boehm, utilised such an additional electrode, and a similar tube has recently been produced by Tozer. Such additional electrodes have chiefly been utilised in electronic tubes and their discussion is therefore most conveniently postponed to a special section.

## THE ANTICATHODE AND TARGET

The terms " anticathode " and " target " are nearly synonymous. Strictly the target is the active portion of metal, of heavy atomic weight, as platinum or tungsten, supported upon an anticathode of cheaper metal, as copper or iron.

The anticathode is also the tube anode, but convention restricts the term " anode " in the gas tube to the accessory electrode just discussed.

The term " target " is used to symbolise that this region of the anticathode is subjected to bombardment, in much the same way that a military target is subjected to a stream of projectiles, and we may press this analogy still further since such a target, under bombardment by a machine gun, would cause the conversion of the kinetic energy of the bullets to sound, heat and light radiation, in much the same way that

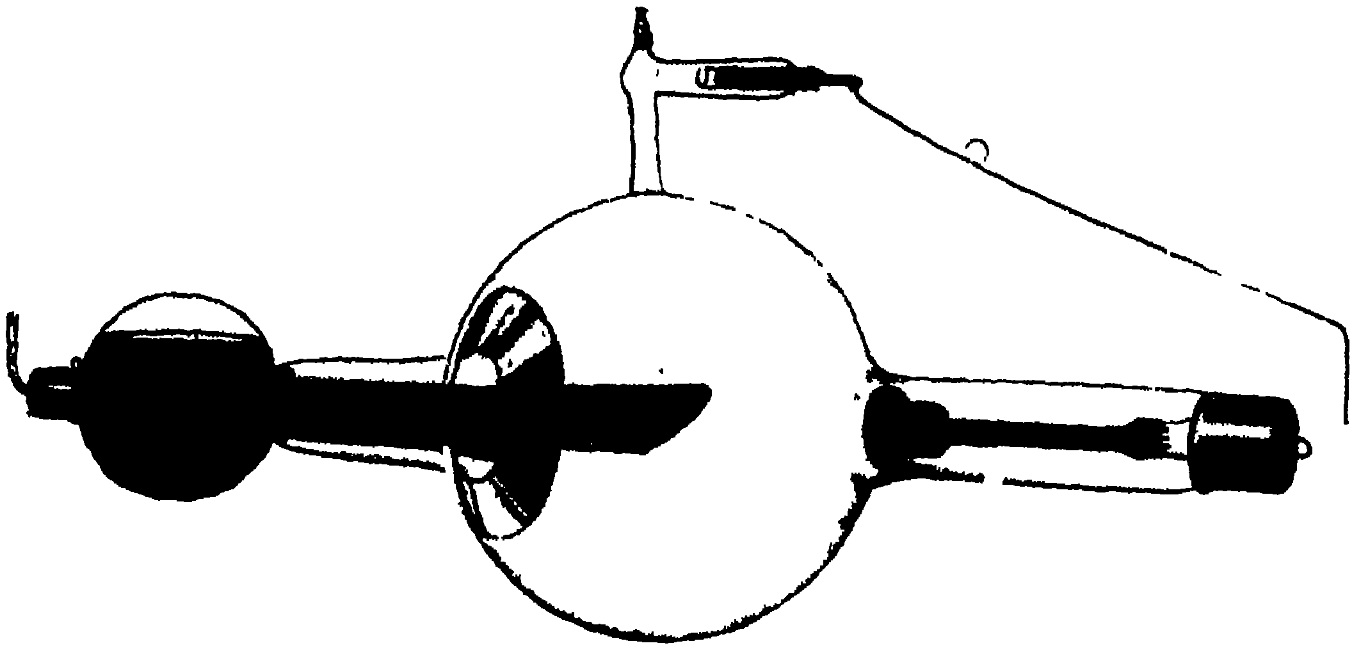


FIG. 76.—Philips Anodeless Tube.

(1)

(2)

FIG. 77 (1) & (2).—Ionic Tube Targets.

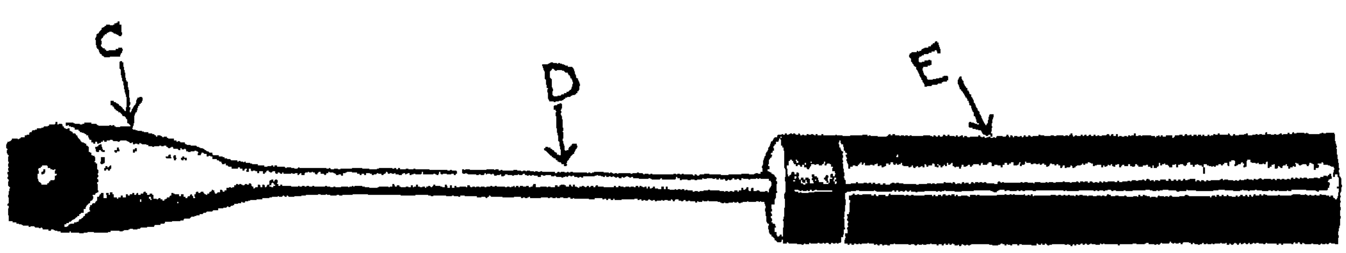



FIG. 77 (3).—Coolidge Tube Target.

[To face p. 101.

the kinetic energy of electrons is converted to X-ray, light and heat radiation. Such an analogy is approximate only and should not be pressed too far.

The form taken by the anticathode and target as shown in Fig. 77.

Upon the oblique anticathode face the button-like target material is mechanically held, or better, fused by casting the common metal around it. The thickness of the target material is usually about 0·1 in. The anticathode head is usually copper, having good electrical and thermal conductivity.

This is in turn carried upon a stem of metal, usually iron. The anticathode stem is usually fitted closely into the glass anticathode sleeve and fixed, to prevent longitudinal or rotational movement, by pressing in the glass, when molten, into several small holes in the metal stem.

To prevent fracture of the glass sleeve due to inequality of glass and metal expansion it is common to have a longitudinal slit (see Fig. 77 (2)) in the iron stem whereby any expansion of the metal can be taken up.

It is also common when an intermediate stem is used, to drill a hole, as shown in Fig. 77 (1). The object of this is to allow passage, of the air within the sleeve, into the bulb during exhaustion, as otherwise, this air might be retained by well-fitting joints and, by gradually leaking into the bulb, spoil the vacuum.

The former use of a globular instead of a flat target face is now abandoned, since it tends to scatter the radiation.

Connection is made to the exterior by means of a platinum wire, and a copper wire may pass from this sealing wire direct to the copper anticathode head. In other cases a copper, nickel and iron alloy, or a chrome-iron alloy, having the same coefficient of expansion as the glass, is used to make external connection. To prevent breakage, as in all such lead-through connections, this wire is surrounded by a metal or ebonite cap, cemented to the glass and having a ring connection.

In the Macalister-Wiggin tube a core of iron is used to make connection *viâ* the glass.

In the Coolidge tube the tungsten target is carried by a fused molybdenum stem D (Fig. 77 (3) ), in turn carried by a split-iron tube E, all the metals being carefully gas freed. It was however found that the molybdenum stem, being of high atomic weight, gave rise to hard radiation, when bombarded by secondary electrons arising from the target. Since such radiation could penetrate the glass tube and, in some cases, gave rise to a very large intensity of non-focal radiation, in the modern Coolidge tubes the tungsten button has a gas-free copper stem cast around it, the soft characteristic radiation of which is absorbed by the tube walls and does not so destroy the focus. At the same time the thermal conductivity of heat from the target is improved.

platino-cyanide fluorescent screens was also nearly universal and the extended use of tungstate intensifying screens had not developed.

Much of the better fluorescent effect of the platinum tube is therefore to be traced to the variations of fluorescent absorption by the platinum-salt screen, with the characteristic platinum radiation of the tube target. Such fluorescent absorption does not occur when a platinum target tube is used with a tungstate fluorescent, or intensifying screen, but does occur when a tungsten target tube is used with a tungstate screen.

There is therefore very sound theoretical reasons to suppose that, with the modern tungstate screens, the tungsten target tube is superior.

Some German X-ray tube manufacturers still use platinum for X-ray tube targets, for example in the Lilienfeld electronic tube.

Whilst osmium and iridium have been used for X-ray tube targets their use has been comparatively small, in spite of the fact that iridium, whilst expensive, is used in the pen industry on account of its great hardness.

The use of thorium and uranium appears to have been first protected by Rentschler and Marden (Brit. Patent 173,238/1920) in 1920, but Coolidge is stated to have used this in 1915.

Still more recently * Coolidge has described the results of practical use of both thorium and uranium, both metals of high atomic weights. Thorium is becoming increasingly cheap owing to its use in the lamp and thermionic valve industry, and uranium is also cheap, but no extended source of the pure metal yet exists.

In operation Coolidge found thorium to show a marked tendency to pit and disintegrate, and is apparently not practicable for the purposes of an X-ray tube.

Uranium, having a low melting point (1,800° C.), can only be utilised on low output tubes. Disintegration, as shown by sparking from the target, occurred and irregularity of operation was apparently due to uranium from the target condensing upon the thermionic filament and so varying its electronic emission. By heating the filament to such a temperature that this condensation no longer occurred, this irregularity of operation was largely avoided.

Measurements of intensity show about 30 per cent. greater efficiency of uranium as compared to tungsten, and the difficulties of operation are attributed by Coolidge to impurities and conditions of operation, who also states it should now be possible to construct a satisfactory high-voltage, high-power tube to give 50 milliamperes at 250 kv. with a uranium target, which would appear to offer advantages in the obtainance of very penetrating radiation, giving a greater intensity of therapeutic depth dose.

We have already illustrated the composite construction of the anti-cathode, to avoid expense of unnecessary expensive target metal.

* *Jour. Frank. Inst.*, 199, pp. 619–648, 1925.

In gas tubes the metal used is invariably copper, or iron, or both, and in electron tubes molybdenum, copper, or iron. Copper would appear to be best in consequence of good electrical and thermic conductivity, and since the K radiation of copper, due to impact of secondary electrons, is so soft as to be absorbed by the glass wall of the tube. It is also easily obtained gas free by appropriate vacuum furnace treatment and can be easily cast around the target. Such composite anticathodes should be actually fused together by casting, as this results in better electrical and thermal conduction, unless the button of target metal is large and great heat will not be developed as in a low-power tube, when the button can be merely held mechanically, since the heat will be radiated directly from the target rather than conducted away by the anticathode, such conduction placing a greater strain upon the anticathode and glass seal.

Holbeach has shown that by deliberate overloading of tubes it is possible to cause the copper in the neighbourhood of the target to actually fuse, so that the target slips out of its socket.

With very high tube loads it is found the target metal tends to crack. This cracking would appear to be less likely when the tube is operated by a constant potential source of energy, than when operated by a varying source of energy, as a rectified transformer current or an induction coil current.

With the latter types of apparatus, owing to the intermittent nature of the discharge, whereby energy flows during the peak values and ceases for the intervals between these peaks, the target is likewise intermittently heated with intervening intervals of cooling. There is in consequence intervening expansion and contraction of the metal, which puts a much greater strain upon the tensile strength of the metal and cracking is more apt to occur, than with a steady rate of heating with a constant source of energy. This is quite analogous to the greater dielectric stress thrown upon an electrical insulator by an alternating potential, as compared to a steady direct-current potential.

As in the case of such electrostatic conduction and in magnetic conduction, in thermic conduction there is a definite difference of thermic potential (temperature difference), above which the strain upon the conductive metal is too great, the metal is overstressed and rupture results.

In order to distribute more evenly the thermic current, or heat flow, and to avoid too great differences of temperature, or heat potential, it is necessary to give the target a certain minimum area and to keep the temperature gradient, or difference of temperature per unit length, within certain critical limits.

When these limits are exceeded and cracking results, these cracks may extend to depths of $\frac{1}{4}$ in. or more and, in a water-cooled tube,

water. may actually so enter the X-ray tube itself, with dangerous possibilities. A tube so cracked during manufacture test is, in consequence, a potential source of danger and should be refused without hesitation, or, if the cracking results by operation, in a water-cooled tube, the tube should be put out of use.

It is this critical limit of heat flow without mechanical rupture, which limits the output of any given tube. If the focus of the cathode stream upon the target is too fine and concentrated, the heat developed is so intense that fusion results, and, in fact, furnaces to fuse highly refractory metals have been constructed upon this principle, notably first by Crookes.

Such a concentration of the electron beam is desired for radiographic tubes in order to give a finely focussed radiation and great photographic

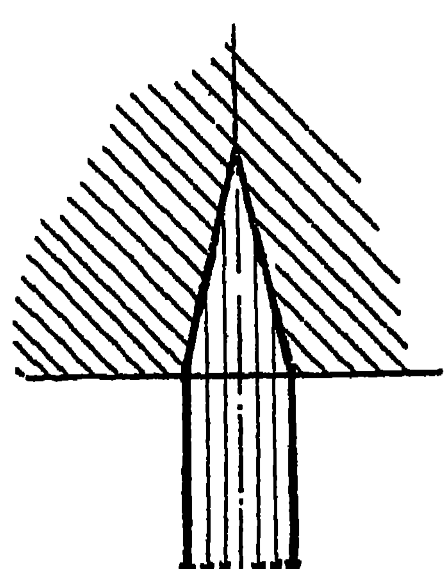


FIG. 78A.

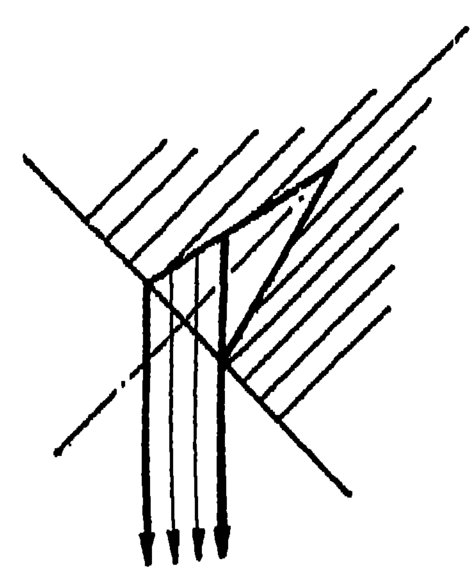


FIG. 78B.

definition, since such a focus tends to give a point source of radiation and absence of penumbra in the shadow cast by any object.

In consequence of such fine focus, the tube is only suitable for brief operation over a period during which the temperature gradient cannot exceed its safe limits. For radioscopic and particularly, lengthy radiotherapeutic usage, such a fine focus is not practicable. In such tubes, to avoid a too sharp focus, the target is not placed exactly at the cathode ray minimum focus point, but just beyond this point, so that the electron stream is distributed over a larger target face area, with greater heat conductive power.

Tubes are in consequence classified as "fine" and "broad" focus tubes with an intermediate "medium" focus tube, partly, but not wholly, partaking of the advantages of the extremes of focus. For very heavy operation current values, the tube must necessarily be a broad focus tube.

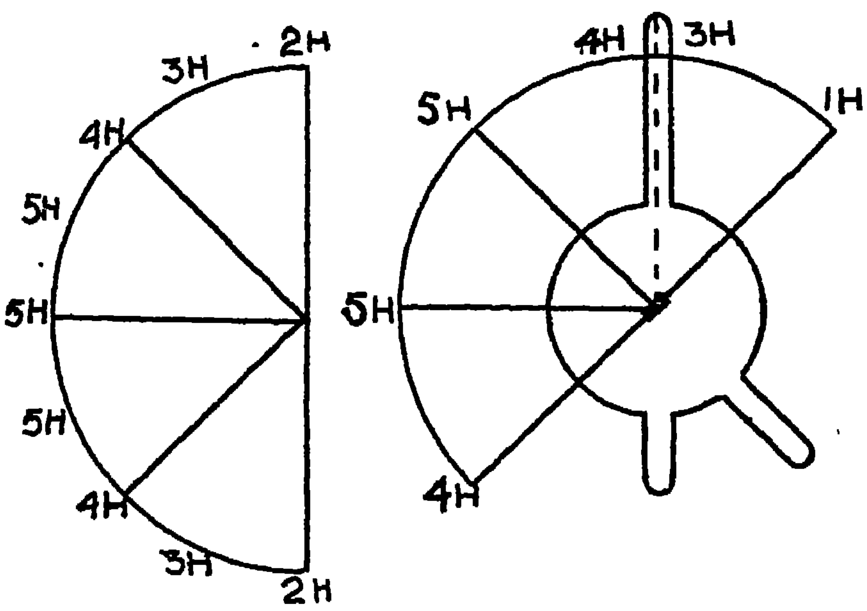
To allow a single tube to have at wish either a fine or broad focus, two cathode tubes have been produced (see p. 93). Müller has very ingeniously produced a single-cathode electron tube in which, according to the load, the focus is automatically varied (see Chapter III.).

Philips (Brit. Patent 237,580/1924), by use of a flat instead of an

inclined target, have increased the effective area of the target by giving this a V, or a hemispherical depression, as shown in Fig. 78A.

It is estimated that with a hemispherical base of 2·5 mm. and a depth of 4·5 mm., the effective target surface is increased fourfold without loss of definition. It is further claimed that if the metal is overheated and vaporised, the metallic vapour condenses upon the cooler portion of the adjacent target and further, that with target and cathode directly opposed the effect of any lack of target orientation is not so great, as is evident from Fig. 78B. Any increase of irregularity of surface of the pit focus also increases the effective metallic surface without loss of focus.

A further advantage of such an arrangement, not claimed by the patentees, would appear to be that with such a target, directly opposed to the electron stream, the radiation produced is also more penetrating,




*a* FIG. 79. *b*

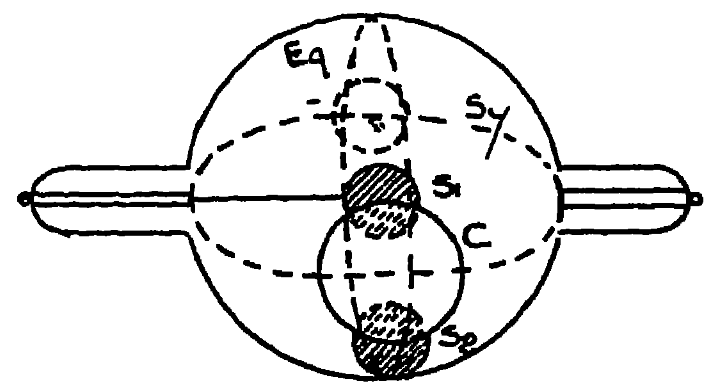



FIG. 80.

it being well known that radiation, radiated perpendicularly to the target, is more penetrative than that radiated at any angle to the perpendicular.

The distribution of intensity of radiation in different directions of the radius of a hemisphere, having the target as the centre of hemisphere base, is shown in Fig. 79, *a*. This has to be determined in respect to two planes, one vertical to the direction of the electrodes along the long axis of the tube (Fig. 79, *a*) and one transverse to this axis is shown in Fig. 79, *b*. These intensities may be directly measured by any suitable intensimeter, of which the Bordier photographic method (Chapter VII., Vol. II.) is usually the most convenient, as it allows a simultaneous record of all regions.

Average values of such measurements are as indicated, where the maximum value is taken as 5H.

The point of most intense radiation and most parallel radiation is at the intersection of the planes, usually termed the *equilateral and symmetrical* planes, shown dotted in Fig. 80. Symmetrically disposed to the *central zone c*, in the equilateral plane, are two *symmetrical zones* $s_1$ and $s_2$ as regards equality of intensity of radiation. It should be noted that, in such largely theoretical intensity areas, which vary in position very greatly

with any irregularity and asymmetry of the anticathode, no account is taken of the effect of polarisation (*q.v.* Vol. II.) which is always existent in X-radiation and which causes the intensities to differ in the various quadrants of the beam circle with the focal spot as centre. The proposal to rotate continuously the X-ray tube (R. Pohl, Brit. Patent 7,761/1914) for purposes of treatment to avoid burns appears therefore to be based, and apparently without intent, upon very rational grounds, as such rotatory movement would overcome the inequality of distribution, which must always result owing to the existence of polarisation in the X-ray beam.

Kaye and others have shown that the radiation of an X-ray tube is more penetrating and more intense if this is observed in the direction of the cathode stream, *i.e.*, in the region of the longitudinal axis of the tube. Wagner and, independently, Duane, by means of spectrographic measurements, have confirmed this fact and found that, although the minimum wavelength always remains the same, and so confirms the Einstein-Planck relation $Ve = h\nu$, the position of the maximum intensity of the intensity and wavelength curve moves towards the region of shorter wavelength and more penetrating radiation, as the longitudinal tube axis is approached.

The physical reason for this variation of average wavelength is doubtless as follows. If an electron approaches and collides with an X-ray tube target placed transversely to its direction of motion, it will tend to give out all its kinetic energy as energy of radiation, since it can only rebound from the target and is largely prevented from so doing by the repulsion of oncoming electrons of equal energy behind it. Such is the case if the target is directly perpendicular to its direction of motion.

If however this target is inclined to the direction of motion, the electron will collide with the target surface at an angle and, in consequence, will be reflected from the target with more or less partial loss of its kinetic energy and will so be removed without total energy loss from the region of the target. In other words, instead of the electron being brought entirely to rest, we have a " recoil " electron which carries away part of its original energy. Since this energy is, in consequence, not available for conversion to energy of radiation, it follows that an inclined target in an X-ray tube must be less efficient than a perpendicularly placed target.

The Philips target (Fig. 78A) should, in consequence, give rise to a more general penetrating radiation, than if this were inclined to the electron-stream direction.

Such perpendicularly placed targets have been often previously utilised, for example by Owen * in the ionic tube. Owen used a sheet of silver ·1 mm. thick soldered to a ring of copper, the latter being water-cooled.

* *Proc. Roy. Soc.*, 86, p. 426, 1912.

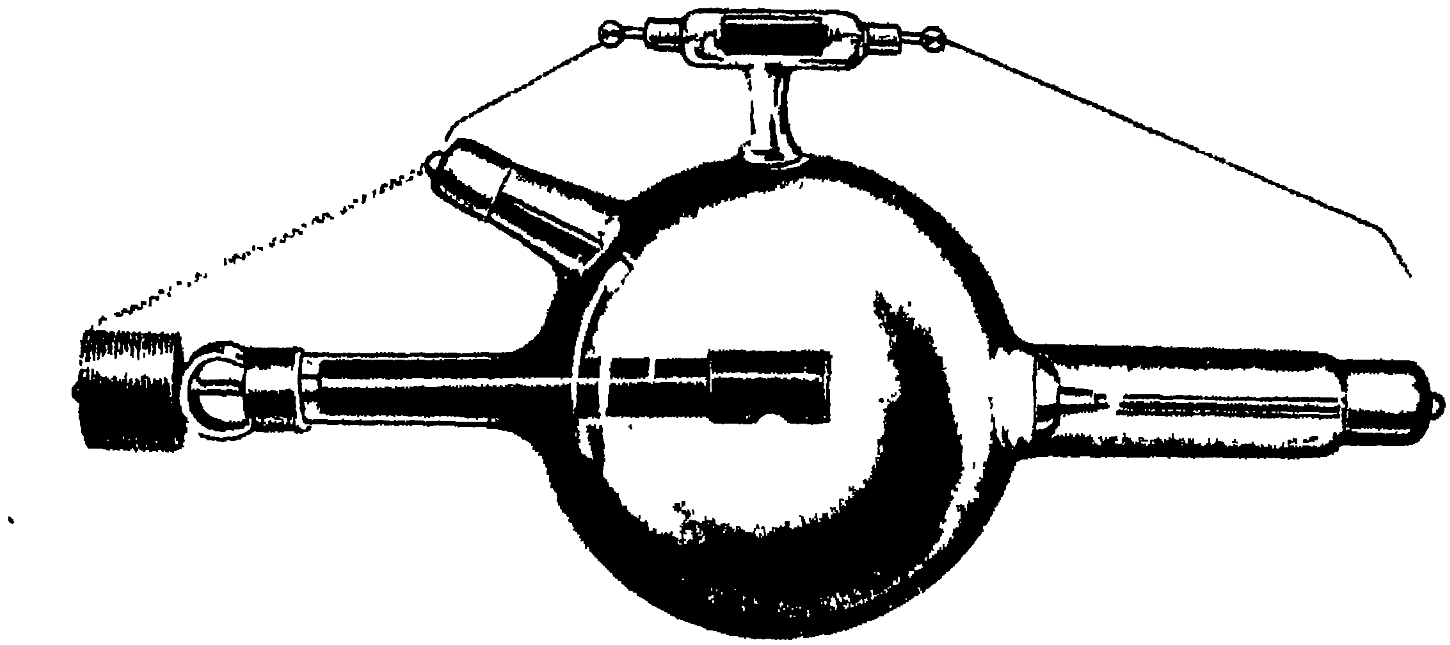


FIG. 81.—"Constance" Tube with Anode Hood (Messrs. Gundelach).

[To face p. 109.

Coolidge (Brit. Patent 108,793/1916) in his metal tube (Figs. 147A and 147B) also used such a directly opposed arrangement of cathodic filament and target, *viâ* which the radiation passes to the exterior of the tube.

Where the radiation passes directly *viâ* the target itself, as in the arrangement of Owen and of Coolidge, the softer components of the radiation must be very greatly filtered out by the target metal and the exterior radiation is highly filtered penetrating radiation, as desired for deep therapy, for which purpose radiation filtered by silver is very suitable.

This method of improving the radiation quality unfortunately rapidly fails, since to produce an intense radiation, with the expenditure of great energy, a massive target is imperative on account of the heating effect, and the target soon reaches a thickness at which even the harder radiation is totally absorbed.

In many X-ray tubes the anticathode will be found to be surrounded by a glass sleeve (Fig. 45). In modern tubes this sleeve is comparatively little seen, now that the transformer has largely replaced the induction coil for purposes of excitation. The purpose of such a sleeve was to prevent the anticathode from acting as cathode during the passage of inverse current when the induction coil was used for excitation. Such inverse current gave rise to very soft radiation both owing to the smaller value of inverse voltage and to the aluminium, of low atomic number, acting as an inefficient anode, as regards X-radiation excitation. Such soft radiation, absorbed by the glass wall and causing great heating, was focussed upon the glass bulb behind the normal anode and was very liable to fracture the glass in the region of its focus. The provision of the glass sleeve, like the corresponding cathode sleeve (*q.v.*), caused the reversed electron stream to be focussed upon the centre of the normal cathode and the greatest intensity of the soft X-radiation to be directed against the refractory target and very little radiation to fall upon the glass walls.

In many tubes this safeguard was still further improved by making a hole in the glass sleeve opposite the accessory anode, so allowing the inverse current flow to pass from the metal anticathode stem to this electrode, with very inefficient X-radiation generation and absence of heating.

*Anticathode Hoods.*—A method of producing a sharp focus in an X-ray tube, without restriction of the area of the focal spot on the target. with consequent restriction of power, is by means of some form of anticathode hood.

This method is by no means new, but has been used since the early days of radiology, notably by Gundelach, whose "Constance" gas tube is shown in Fig. 81. It was later used in the electron tube by Coolidge, a sectional view of his hood being shown in Fig. 82 (Brit. Patent 10,454/1913). Internal tube screens for the same purpose were also proposed by Tousey in 1911 (Brit. Patent 7,067/1911).

The actions of such hoods are as follows ;—

(1) Acquiring a highly negative change, their walls tend to repulse the negative electrons approaching the target and, by so restricting the area of the cathode stream, to give a much sharper focus of electrons upon the target.

(2) Since the metal of which they are formed has sufficient thickness to absorb the radiation, the only radiation which can emerge from within the hood is *viâ* the small hole in the lower surface, and the radiation then emerges as from a restricted source of origin, equal to the hole, widely divergent radiation being suppressed. The focus is thereby further improved.

(3) The hood was particularly used by Coolidge* in order to prevent loss of focus due to radiation from secondary electrons. Such secondary electrons rebounding from the target are, owing to the negatively charged wall and negative space charge, unable to pass away from the target, and eventually fall back upon the anode, to produce further radiation.

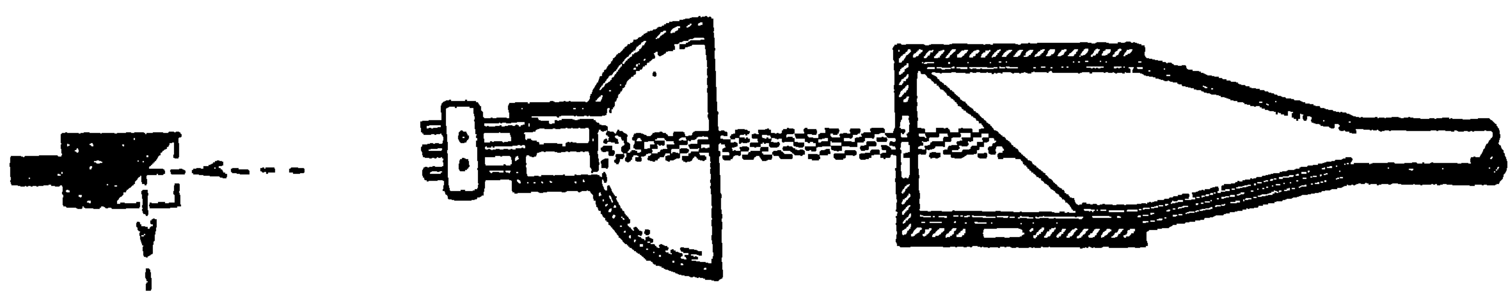


Fig. 82.

As they strike a wide area of the anode and target they produce badly focussed radiation, as well as soft unuseful radiation. The hood, in consequence of its negative charge, largely prevents the emission of such secondary electrons, as well as preventing their passing over a large trajectory, as they are strongly repulsed by the negatively charged hood walls. Such hoods have been used for a converse action, namely, by suitable arrangement of the hole of emission *d* (Fig. 83), to allow only secondary and not focal radiation to emerge from the hood (Polyphos Company, Brit. Patent 20,100/1905).

(4) In the gas tube, this hood, by preventing the passage of positive ions except *viâ* the axial path, resulted in absence of radiation upon the weak glass cathode neck, which might result in fracture and, in this respect, was similar in action to the shield ring already described (p. 66).

(5) In induction coil excitation the hood itself tends to prevent passage of inverse current, by acting as an inefficient cathode when inverse current passes.

(6) The hood, by intercepting metallic particles sputtered from the target, prevents the bulb from being blackened. This is of particular importance in the high voltage tube, where sputtered metal causes irregularity of operation.

* *Amer. Jour. of Rönt.*, 21, p. 882, 1915.

(7) In the event of the target becoming excessively hot and loosened from the surrounding more fusible anode metal, the hood prevents this hot metal falling upon the glass, with risk to the patient below.

(8) A larger anticathode area being produced by this accessory portion of the anticathode, more efficient radiation of heat and cooling results.

Coolidge states the effect of such hoods is less upon small-sized tubes than upon larger tubes.

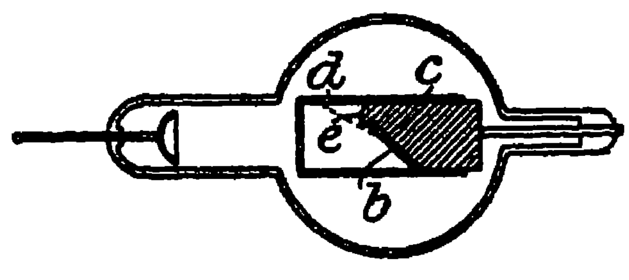



FIG. 83.

The hood is preferably made of some light metal giving an easily absorbed soft X-radiation when struck by secondary electrons, but of sufficient thickness to absorb completely all non-focal radiation. Coolidge specifies however a hood of tungsten or molybdenum.

In a more recent patent (Brit. Patent 236,208/1923) the effect of such a hood is obtained by recessing the anticathode face and placing the target T at the bottom of the recess with a suitably disposed window E for radiation emission (Fig. 84). Siemens and Halske (Brit. Patent 181,903/1921) surround the target by a bell-shaped hood 3 (Fig. 85) of silica, attached to the cathode and extending from the cathode to a shield 7

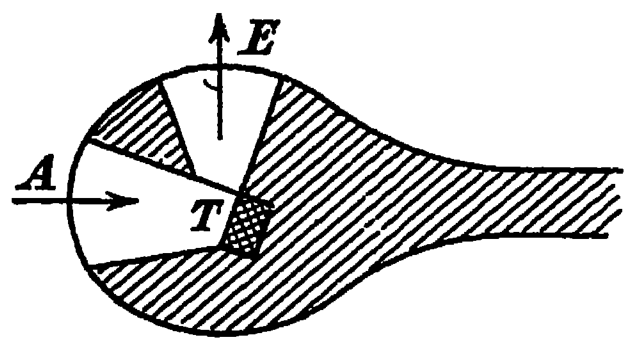



FIG. 84.

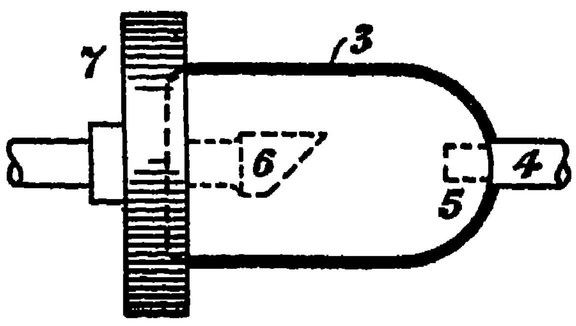



FIG. 85.

behind the target. The purpose is to prevent secondary radiation from the target impinging upon the walls of the X-ray tube. An opening is

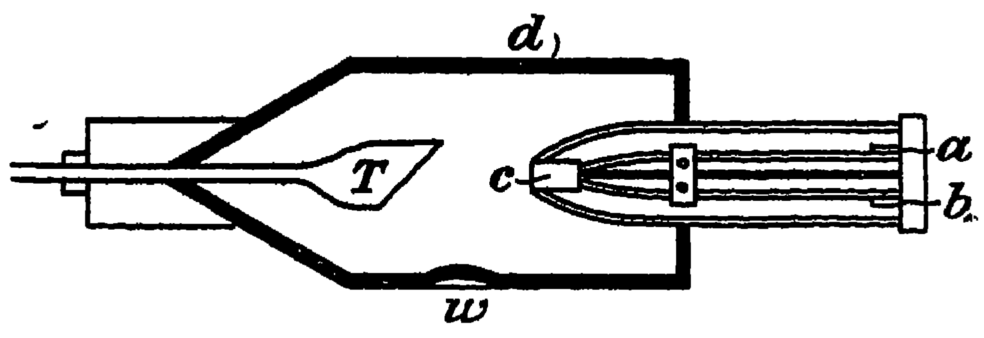



FIG. 86.

present to allow the passage of X-radiation in a desired direction. It is stated that the shield may have upon it, to render it conductive, a film of tantalium or other metal, but that in consequence of its highly charged condition the silica may actually be rendered conductive without such a deposit.*

* In the practical types of this tube (*Fort. auf. dem. Geb. der Rönt.*, 35, p. 636, 1926) the hood is made of a heavy copper-tungsten alloy to suppress, for protective purposes, non-focal radiation, and the focal radiation is emitted by a metallic beryllium window (see Appendix II.).

A similar arrangement (Fig. 86) has recently been protected by the Research Laboratory of the Royal Arsenal (Brit. Patent 246,194/1925), in which the metal shield *d* surrounds the anode to prevent the bombardment of the glass, and the cathode *c* may similarly be surrounded by a steel shield which has no sharp edges, in order to prevent auto-electronic emission (*q.v.*). Such applications of this hood appear to be in the direction of restricting the electronic paths directly between cathode and anode and, by preventing their passage to the tube's glass wall, to decrease the electrostatic charge upon this and risk of resulting fracture.

A still more pretentious method of restricting the X-ray beam in cross-sectional area is that of Philips, who actually insert a metallic iris diaphragm within the tube itself (see Appendix II.).

## METHODS OF COOLING THE TARGET

We have already stated that of the applied energy that portion which appears as X-radiation in an X-ray tube is very small, in comparison to that emitted as heat and, to a less extent, as light, and has been variously estimated at $\frac{1}{1000}$ to $\frac{1}{10000}$ of the applied energy.* If volatilisation and fusion of the target is to be prevented, the removal of this undesired heat energy is therefore of prime importance.

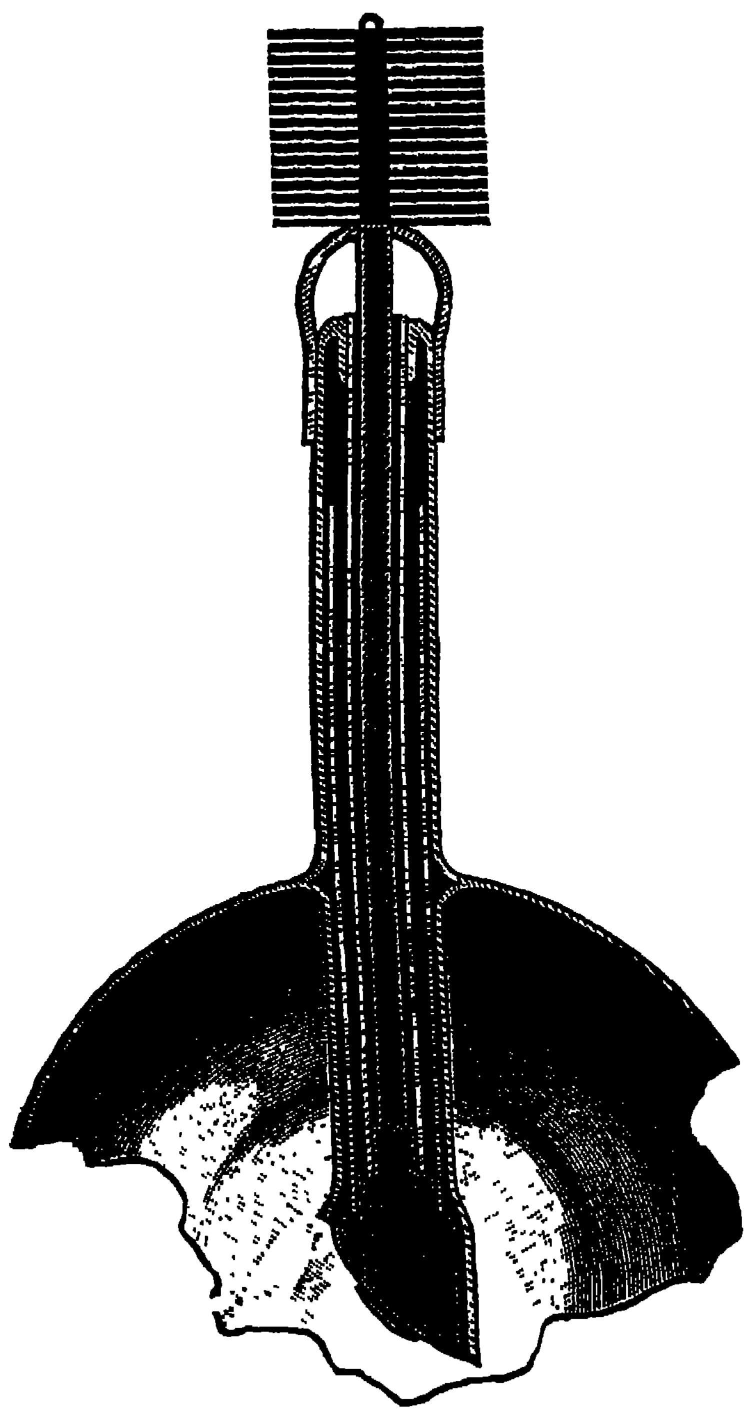


FIG. 87.—External Radiator Tube (Messrs. Gundelach).

It is well known that heat energy may be propagated from point to point by three phenomena, namely by;

(*a*) radiation,
(*b*) convection,
(*c*) conduction,

and all three of these modes of transmission are used, either singly or combined, to remove heat from the X-ray tube target.

*Removal by Radiation.*—This method of cooling is shown in Fig. 87, and consists of increasing the normal radiation of the anticathode, by inserting into the sealed hollow anticathode a rod of metal, which, passing to the external atmosphere, conveys heat from the

* The most recent work is that of Kegerreis (*Phys. Rev.*, 29, p. 775, 1927), who finds a ratio of X to heat radiation of 0·0032 for an electron tube. The ratio is necessarily dependent upon the actual tube as well as its type.

anticathode head to the exterior, where it is either directly radiated, or removed by external air conduction currents. To increase greatly the effective radiating area the external portion of this rod is given a finned form as shown.

This method of cooling is very much used in the ionic tube, as well as in the electron tubes of the Coolidge and Philips types. It has the great advantage over the water-cooling method, later described, in that there is no restriction in the position of the tube during practical use, but, in comparison to this method, the cooling process is much less efficient.

The Westinghouse Lamp Company of America (Brit. Patent 222,454/1923) have suggested the use of internal fins (Fig. 88) in order to increase

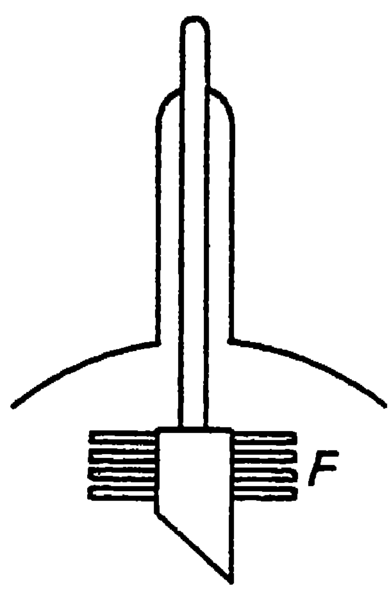



FIG. 88.—Internal Radiator Tube.

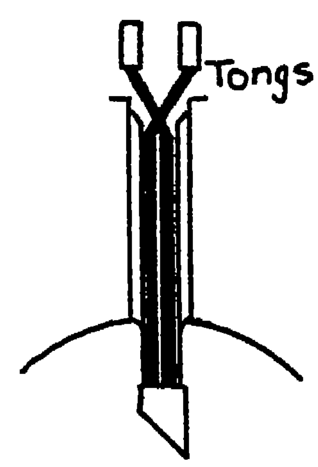



FIG. 89.—Radiator Tongs.

directly the effective radiation of the anticathode, a method previously used by C. D. Miller * in a special Coolidge tube for soft radiation.

In the use of all fins for radiation it would be well, to avoid unnecessary brush discharge, to increase the thickness of each fin and to give it a more rounded edge. As however the method is not sufficiently effective, to remove the heat developed in heavy power high-voltage tubes, this is of less importance, but no less desirable, in smaller power diagnostic tubes.

A method of cooling known as "radiator tongs" depends essentially upon conduction rather than primary radiation.

*Conduction Methods.*—Conduction methods of cooling the target fall into two classes;

(*a*) Those in which the mass of the target is directly increased.

(*b*) Those in which, by special artifices, the mass of the target is not increased, but the heat energy is distributed over a greater area of metal.

The method known commonly as "radiator tongs" is an example of the former method. Whilst this method, due to Müller (Brit. Patent 23,325/1911), may be combined with the use of actual radiator fins, the actual removal of heat is dependent upon the introduction, into a hollow anticathode stem, of a heavy pair of metal tongs (Fig. 89).

* *Phys. Rev.*, 8, p. 329, 1916.

These tongs acquire heat by direct conduction from the anticathode and, when they have attained a certain rise of temperature, are removed and replaced by a cool pair of tongs. This method is only applicable to comparatively low power tubes, as the inconvenience of this method during long-continued tube operation for treatment, or screening, is obvious.

It has advantages over the water-cooling method since it allows the use of the tube in practically any position, but is by no means as convenient as the true radiator method.

The necessity of cooling the X-ray tube target arises due to a local concentration of the cathode-stream energy and resulting concentration of heat. This development may be so great that the rate of heat production is greater than the rate of heat loss, so that the localised heat energy increases in value, to fuse finally the target metal.

Various methods have been suggested to increase the effective target area by giving it a movement relative to the cathode stream, so as to

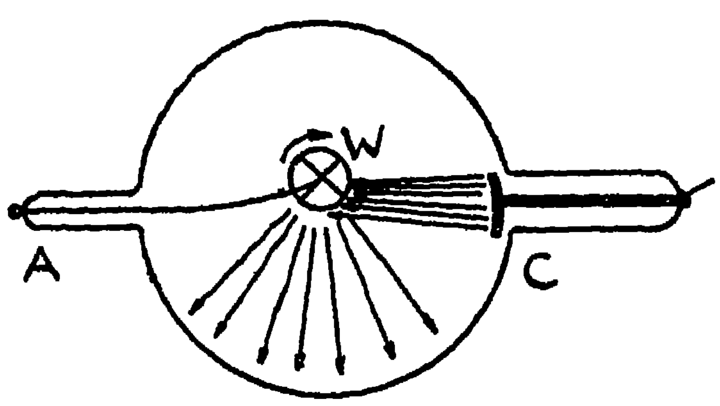



FIG. 90.—Rotation of Tube Target.

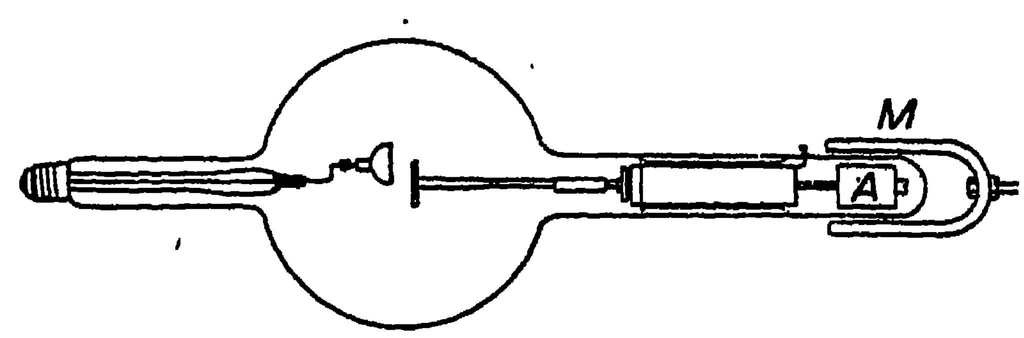



FIG. 91.—Rotation of Tube Target.

bring continually a fresh cooler portion of the target metal beneath the cathode stream bombardment.

One of the oldest of these methods is that of The British Thomson-Houston Company (Brit. Patent 21,389/1914) (Fig. 90), in which the cathode stream is made to give oblique impact upon a wheel W mounted upon graphite bearings capable of rotation under the electronic impacts and, by such rotation, continually bringing a fresh area of the wheel periphery beneath the electron stream.

A further method (Fig. 91), based upon a suggestion of Elihu Thomson, has been actually used by Coolidge,* in which a soft iron armature A is enclosed within the tube itself, in the anode sleeve, and is set into rotation by Ferraris currents, due to external magnetic fields as from M and so causes rotation of a flat target before an eccentrically placed filamentary cathode. Such tubes have been operated by Coolidge at 750 r.p.m. with a circular movement of the focal spot around a circle of $\frac{3}{4}$-in. diameter, and allow a three-fold energy input to the tube. Coolidge states that to justify the complications of this method, such as bearing complications, a tenfold permissible energy input would be necessary, but that this increase could be attained (see also Appendix II.).

* *Amer. Jour. of Rönt.*, December 2nd, p. 882, 1915.

A means to overcome the inherent defects of this method is due to the same company (Brit. Patent 9,428/1915) in which (Fig. 92) the eccentric deviation of the cathode stream from a cathode 4, upon a truncated tungsten cone 2, is effected by rotation of the tube, whilst the cathode stream is magnetically deflected by the solenoid 20.

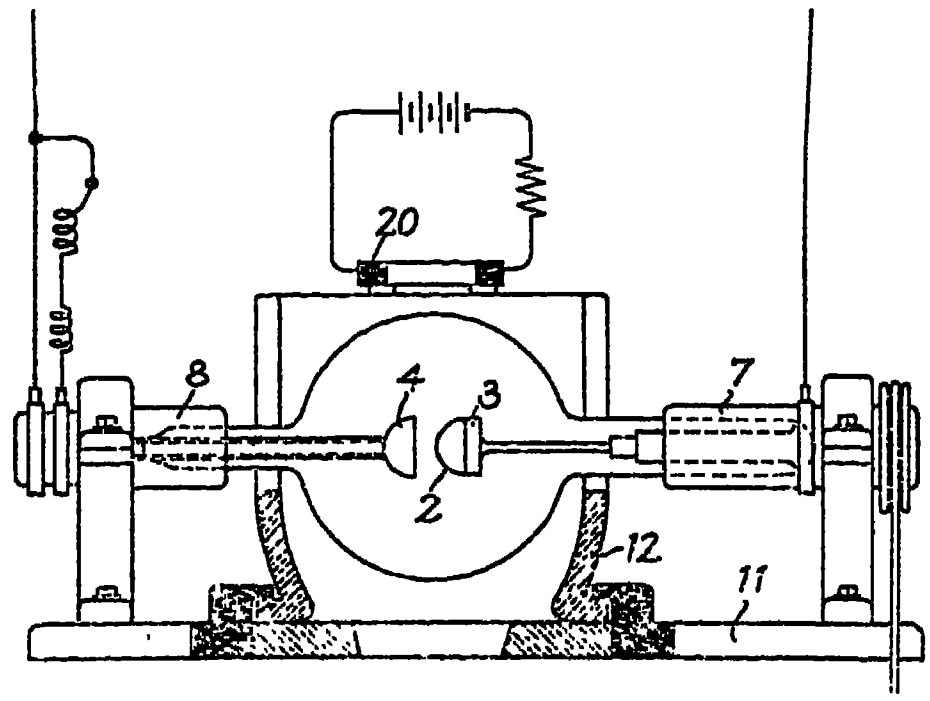


FIG. 92.—Deflection of Cathode Ray by Magnetic Field and Rotation of Tube.

The converse but more complicated method has been used (Fig. 93) by the Research Laboratory of the Royal Arsenal (Brit. Patent 199,831/1922) in which the cathode stream is fixed in space by means of solenoids, and the tube is given the motion of a conical pendulum around its longitudinal axis by a somewhat complicated mechanical system utilising a universal joint and an eccentric bearing.

Sleperin (Brit. Patent 195,594/1923) has suggested the use of similar external magnetic fields of varying intensity and due to polyphase currents, not for the purpose of more efficient cooling, but in order to give the electrons of the cathode beam a spiral path with, it is claimed, by virtue of the correctly applied rotating magnetic field, an increase of electronic

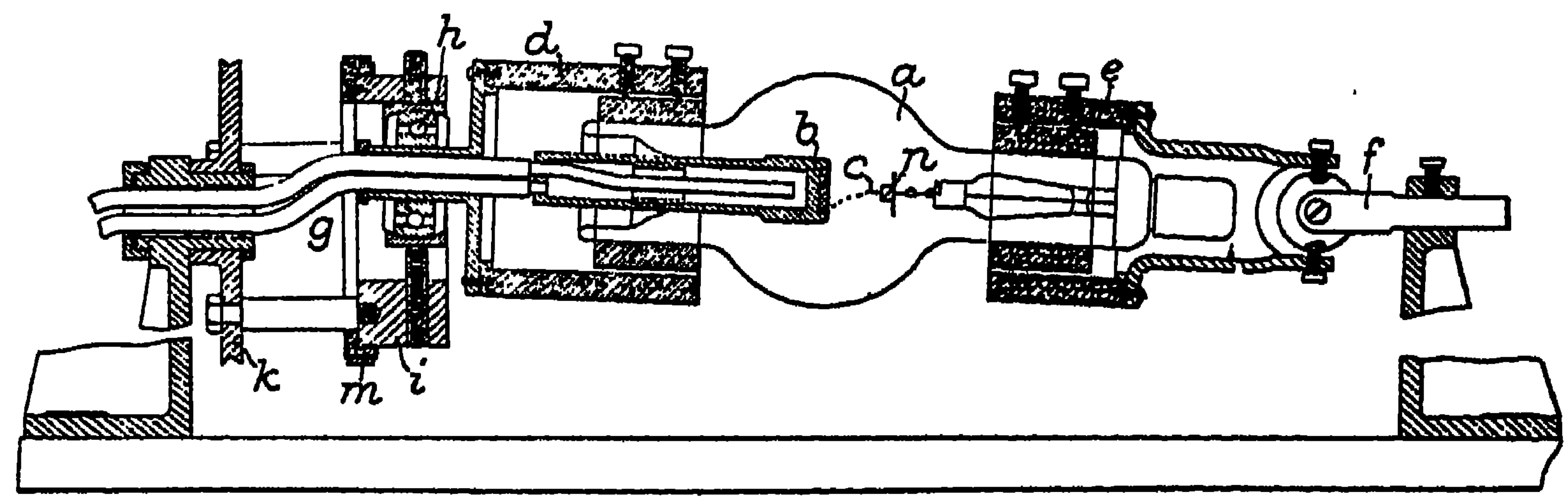


FIG. 93.—Deflection of Cathode Ray by Magnetic Field and Rotation of Tube.

kinetic energy* and an improved X-radiation in the direction of shorter wavelength. Consideration of the relationship ;—

$$\tfrac{1}{2}mv^2 = Ve = h\nu,$$

shows that if we can increase the velocity $v$ of the electrons by any external means, then their value for radiation production must be greater and equivalent to a greater value of V. Sleperin claims that his proposed method would allow X-radiation of equal quality to be generated at lower voltages, with consequent practical advantages. Whilst the method

* The effect of a magnetic field upon the discharge of an X-ray tube was early investigated by Campbell Swinton (*Nature*, 54, p. 238, 1896).

is fundamentally sound, there are no published results of its practical operation.

*Convection Methods.*—The convection method of cooling offers greater difficulties of operation but, having the advantage of greatest efficiency, it is used in the majority of high-energy therapeutic tubes and, of recent years the purely convective circulation of fluid has been assisted by forced circulation within the hollowed anticathode.

The earliest patent is that of Mare (Brit. Patent 5,077/1901) who passed a current of water *viâ* both cathode and anticathode by means of a pair of motor-driven rotary pumps.

In 1908, Rittershaus and Bautze (Brit. Patent 21,577/1908) suggested the circulation of water, or air, directly through the X-ray tube and a central anticathode, by an arrangement shown in Fig. 94 and a similar arrangement has been suggested by Bombe (German Patent 205,757).

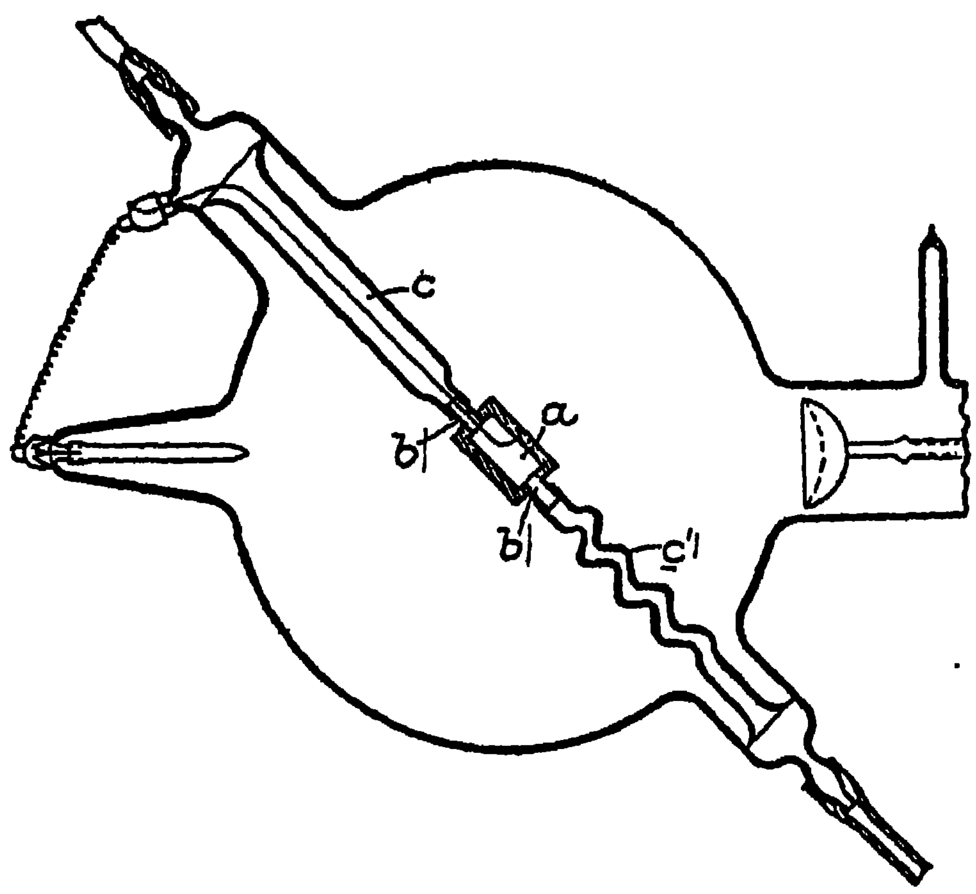



FIG. 94.—Method of Cooling Anticathode.

A further early patent is that of Baret and Gaiffe (Brit. Patent 6,833/1911), in which gas is played directly upon the reverse and external side of the X-ray tube target. In view of its lower specific heat, air cooling has been comparatively little used, in comparison tc water cooling. Lindemann (French Patent 475,688/1915) has suggested the use of mercury, instead of water, by virtue of its much greater specific heat and capability of heat absorption.

With water cooling the removal of heat energy is so effective that it allows the reduction in size of the bulb, as this is not so greatly heated by direct-heat radiation, with consequent economy of space, decrease of the weight of surrounding protective material and greater mechanical rigidity of the tube.

Water-cooled tubes fall into two classes, known as "water-cooled" and "boiling-water" tubes. The distinction is not very clear and the divisions tend to overlap. In the simple water-cooled method, the water may only undergo a moderate temperature rise, whereas, in the boiling-water method, the water actually boils during normal use.

The advantage of the boiling-water method is stated by Dauvillier to be that it keeps the copper of the anticathode at a temperature at

which gas is not evolved, but the non-boiling method would appear to have equally this advantage.

It would however appear that, in consequence of the large latent heat of evaporation of water, if arrangements are made to allow the water to actually boil and condense and not only to be heated, then a smaller volume of water will be more effective than a larger volume of non-boiling water, with consequent space economy.

The simplest form of water cooling is shown in Fig. 95, where the arrangement is obvious. When the water is allowed to boil, danger of fracture of the glass may occur, owing to the liability of "bumping" as the water boils. It is well known in chemical work that such bumping

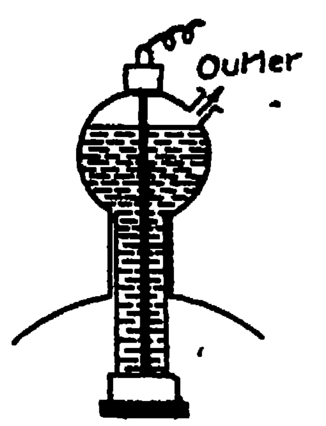


FIG. 95.—Water-cooled Tube.

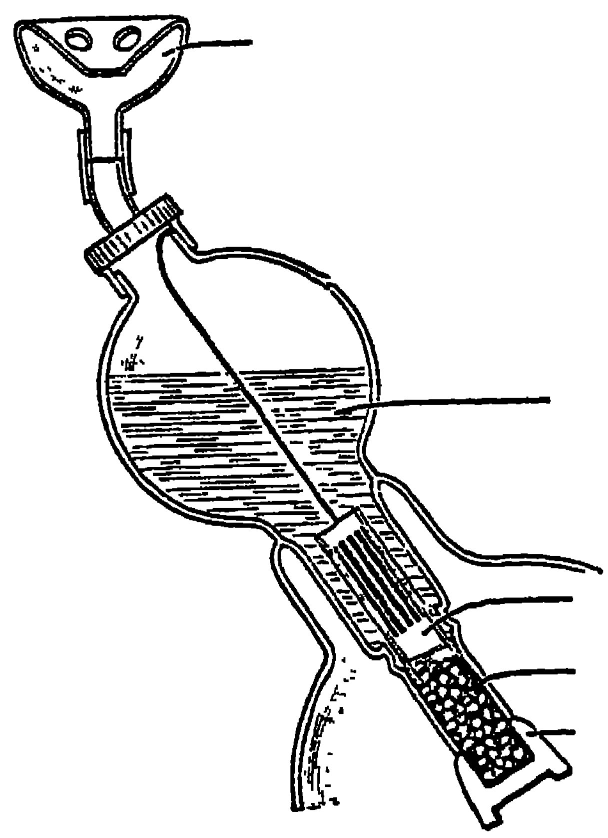


FIG. 96.—Method of Preventing Irregular Boiling (Messrs. Gundelach).

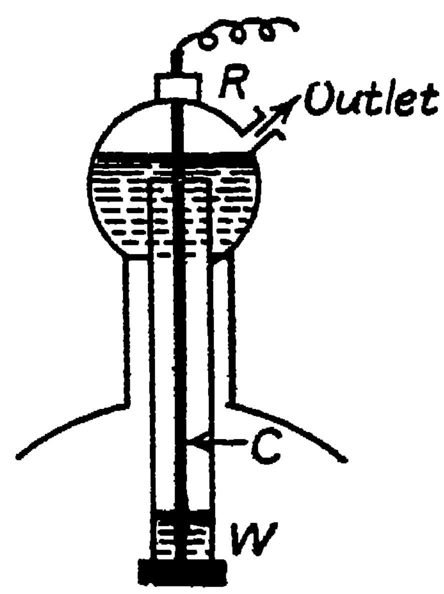



FIG. 97. — Hertz and Philips Cooling Method.

of solutions can be prevented by the introduction of glass beads, which prevent explosive local overheating of the fluid.

Gundelach (German Patent 332,894), in order to prevent bumping in the boiling-water tube, has introduced such beads into the hollow anti-cathode of the X-ray tube (Fig. 96). For this method it is also claimed that the water directly behind the target face is more quickly brought to the desired region of boiling point, since convection of water is hindered by the glass beads, and, it would appear, greater virtue of boiling water over cold water, for the purposes of cooling, is thereby inferred.

Hertz and Philips (Brit. Patent 203,266/1922) have introduced a tube in which an inner chamber is fitted (Fig. 97) to the usual water cooler. Water W in the inner chamber C, under reduced pressure, is caused to boil, and the steam then acts very efficiently, by virtue of its high latent heat of evaporation, to absorb heat from the region of the heated reverse side of the target and to convey this heat to the cooler distal end where, by condensation, the heat is transferred to the externally open water.

Great regularity of action is claimed for this tube and, it is stated, the cooling efficiency is one hundred times greater, but in spite of this its use has not become general. Care must be taken that the outer water chamber is always filled before operation, as otherwise a dangerous explosive pressure may arise in the middle chamber.

The water-cooling method is often combined with other methods, for example, the radiation method, as shown in Fig. 98, where the boiling water is re-condensed by circulation *viâ* a radiator fin system. Other tubes, as Fig. 45, may have a water-cooled anode and a radiator-cooled cathode. Müller (Brit. Patent 25,612/1905) has protected the use of multiple outlets to the water vessel, so allowing the use of the water-cooled tube in the upright, under, or over couch tube positions according to the particular outlet selected to remain open. Gundelach uses a similar multiple-vent arrangement (Fig. 99).

In all water-cooled tubes it should be remembered that, in the event of the water having been allowed to boil away during operation, the tube

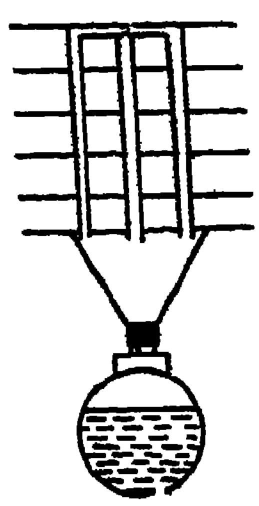


FIG. 98.

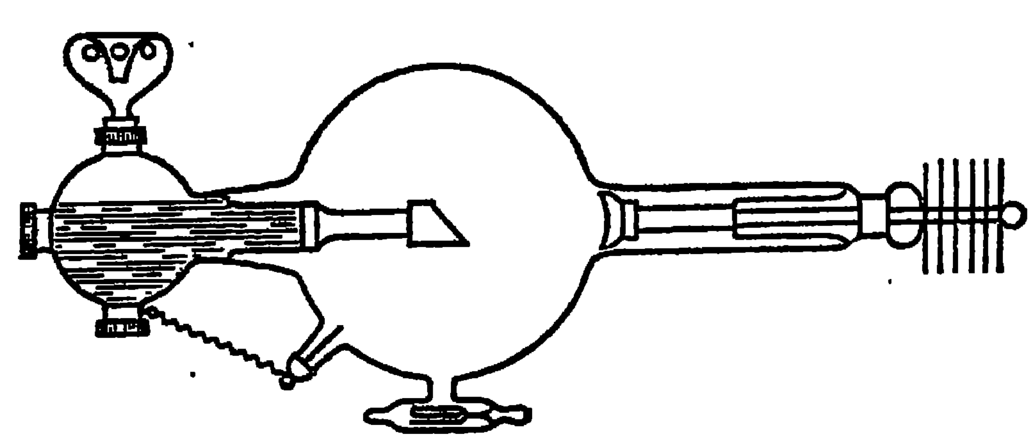


FIG. 99.—Multiple Vent Water-cooled Tube (Messrs. Gundelach).

will invariably crack if cold water is added before the tube has been allowed to cool.

A different method of cooling the X-ray tube by means of water has been adopted by Coolidge and, in practical radiology, by Messrs. Gaiffe, Gallot and Pilon, in connection with oil-immersed tubes. Within the oil container of the X-ray tube holder (see p. 255, Vol. II.) a tubular water-circulating system is introduced. Heat from the tube target is radiated *viâ* the glass walls to the surrounding oil, and the loss of heat from the oil is facilitated by convection in the oil, aided by the system of cooling pipes which, being insulated by the oil from the high-tension tube, can be directly connected to the normal water mains.

This method varies from the more common method in which the forced water cooling is either played directly behind the target or may actually pass *viâ* channels in the metal target itself (Fig. 100).

The simplest and earliest practical form of forced water cooling is shown in Fig. 101 in use with the Lilienfeld tube (a method proposed by Mare in 1901).

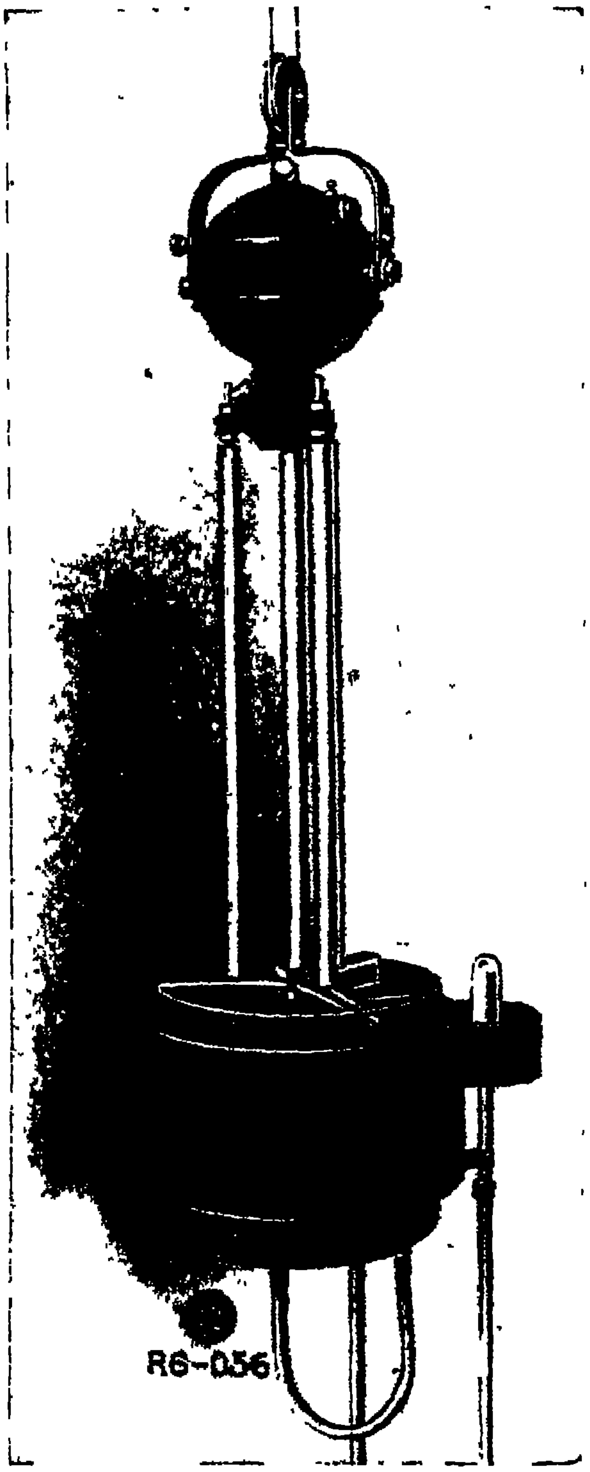



FIG. 101.—Forced Water-cooling System (Messrs. Koch & Sterzel.)

[To face p. 118.

This method consists of a pumping system by which water is forced *viâ* the tube's water ducts by means of an electric motor. As this system must be insulated against the high-tension voltage, the pump is driven by a long insulating spindle connecting the motor and pump.

Such pumps are very effective in operation and are placed above the tube suspended from the ceiling, but should not be placed too near the ceiling or the cooling of the water by radiation is retarded, owing to the greater heat usually present near the ceiling in any room.

Coolidge * has used a more pretentious forced cooling system with his 225 kv., 50-milliampere water-cooled tube, which radiates continuously up to 7 kw. of heat energy.

This is shown in Fig. 102, and consisted of a bronze gear pump *a*, driven by a motor *b*, through an insulating shaft *c*. The water was air-

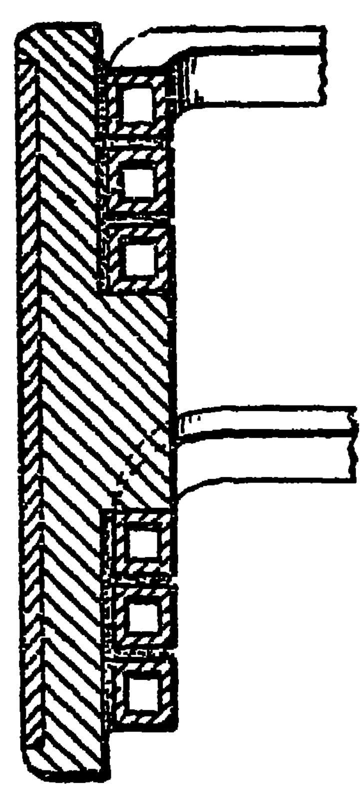


FIG. 100.

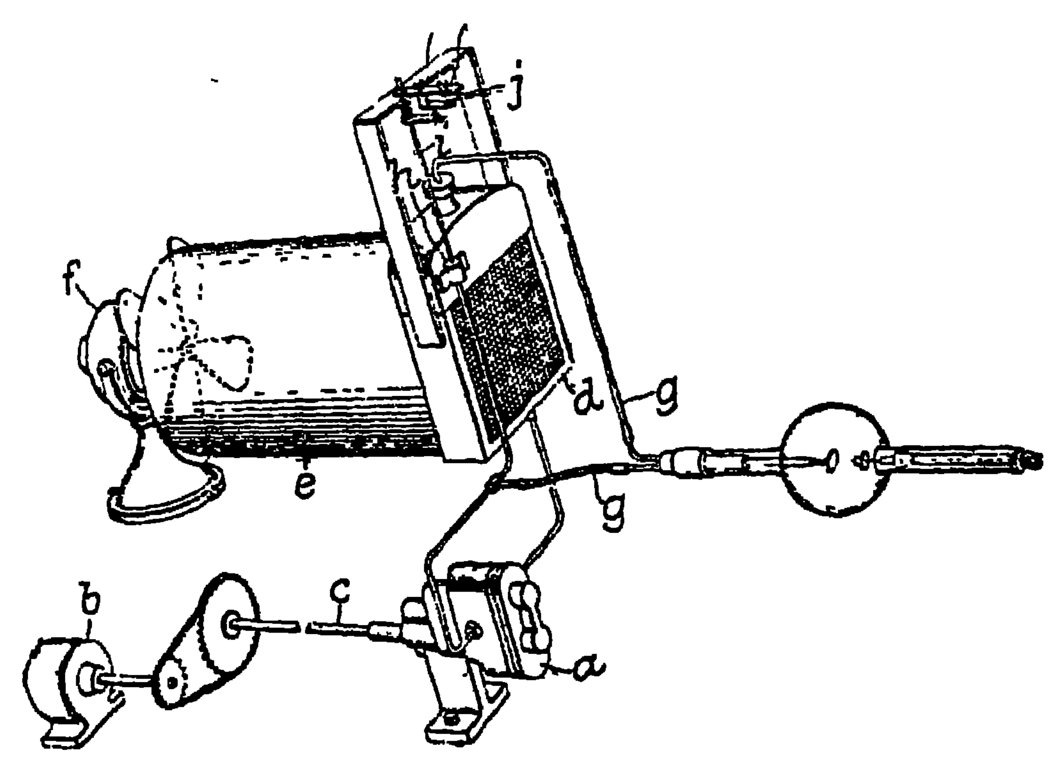



FIG. 102.—Coolidge Water-cooling System.

cooled *viâ* a Ford car radiator *d*, cooled in turn by air, forced through a tunnel *e* made by insulating material, from a fan *f*. The pump was driven at such a speed that it circulated about 4 litres of water per minute through the tube anode at about 30 lb. pressure. With a tube load of 50 milliamperes at 250 kv. the temperature of the water as it left the anode was 70° C., and the temperature was lowered to 50° C. by the radiator.

A gear pump was chosen in preference to a centrifugal pump, because it assured a continuous and not an intermittent flow of water, and furthermore, gave the necessary pressure to force sufficient water through the small ducts in the metal of the anticathode head.

It was necessary to provide some means to guard against failure of the water circulation while the tube was operating, as such failure would involve immediate destruction of the target. This was secured by installing a section of Sylphon tube L (Fig. 103) on the high-tension side

* *Amer. Jour. of Rönt.*, 10, p. 884, 1923.

of the pump and connecting one end of the Sylphon chamber to a rod $f$, operating the contacts $e_1e_2$ in the circuit of a relay which controlled a contactor located in the primary circuit of the X-ray transformer. Details of this device are given in Fig. 104. It is evident from this diagram that unless the contacts $e_1e_2$ are brought together by expansion of the Sylphon tubing $a$, due to pressure of the circulating water, the contactor $c$ will not be operated and current cannot pass through the primary of the X-ray transformer $d$.

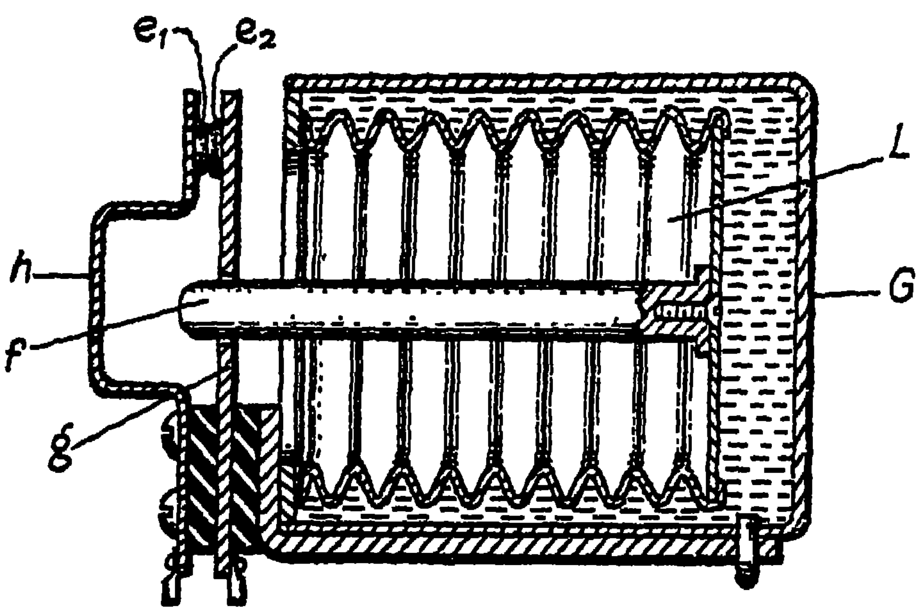



FIG. 103.—Sylphon Pressure Device.

A more finished example of the above system is shown in Fig. 105, in which a motor seen to the right forces, by means of an insulated shaft, water *viâ* the X-ray tube and through a honeycomb radiator, all the water system being mounted upon high-tension insulators.

To protect the deep-therapy tube, the system is equipped with an automatic over-temperature and under-pressure release, either or both of which operate a switch cutting off the transformer current should the temperature become too high or the pressure fall too low. It is also equipped with a pressure and a "water-flow" gauge. The "water-flow" gauge is operated from a small chamber, which receives its pressure from the flow of water *after* it has passed through the target coil of the X-ray tube. A reading on this gauge positively assures the operator of an actual circulation of water *viâ* the tube anode.

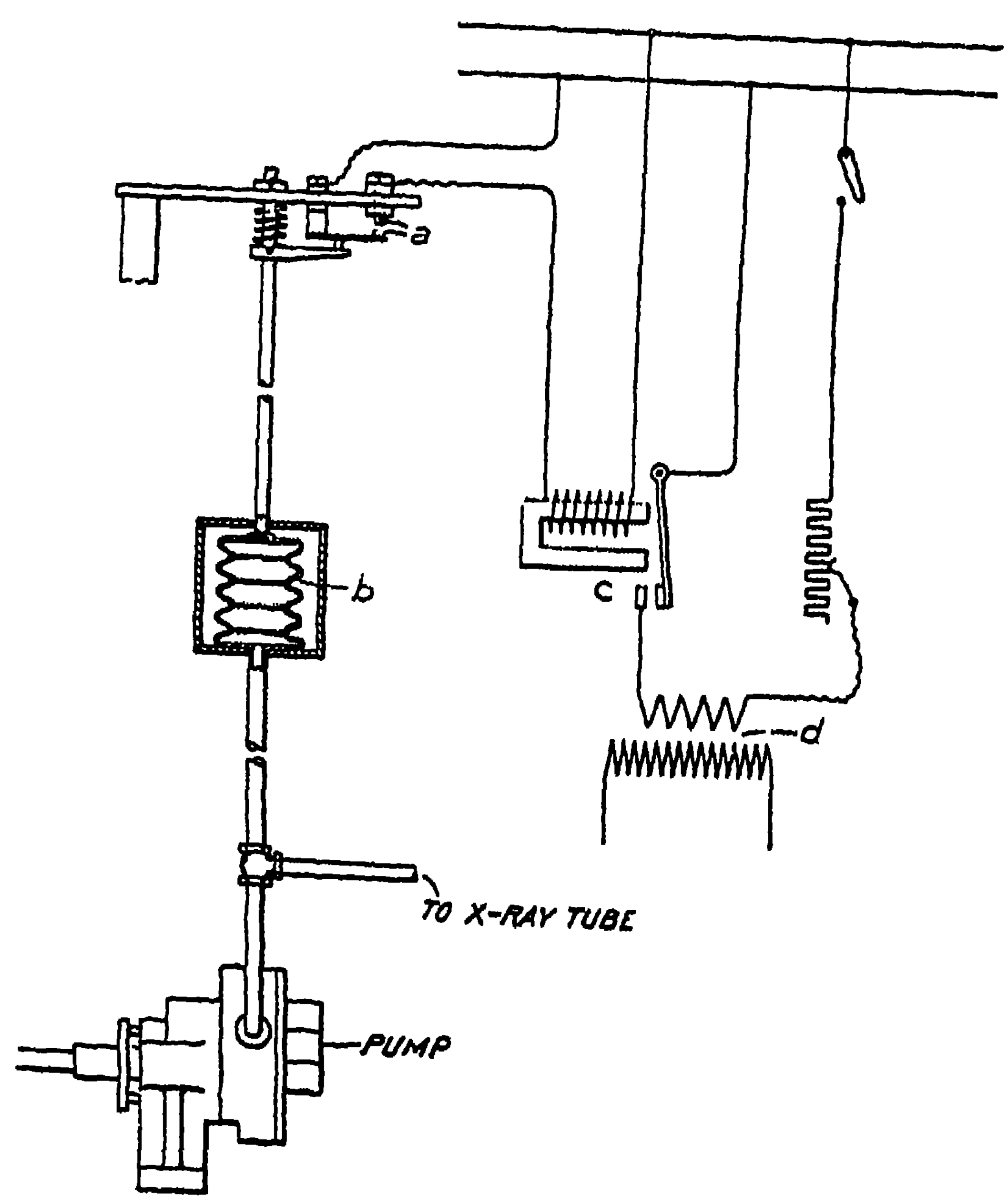



FIG. 104.—Operation of Sylphon Device.

The multi-blade fan is set at the proper distance from the radiator to

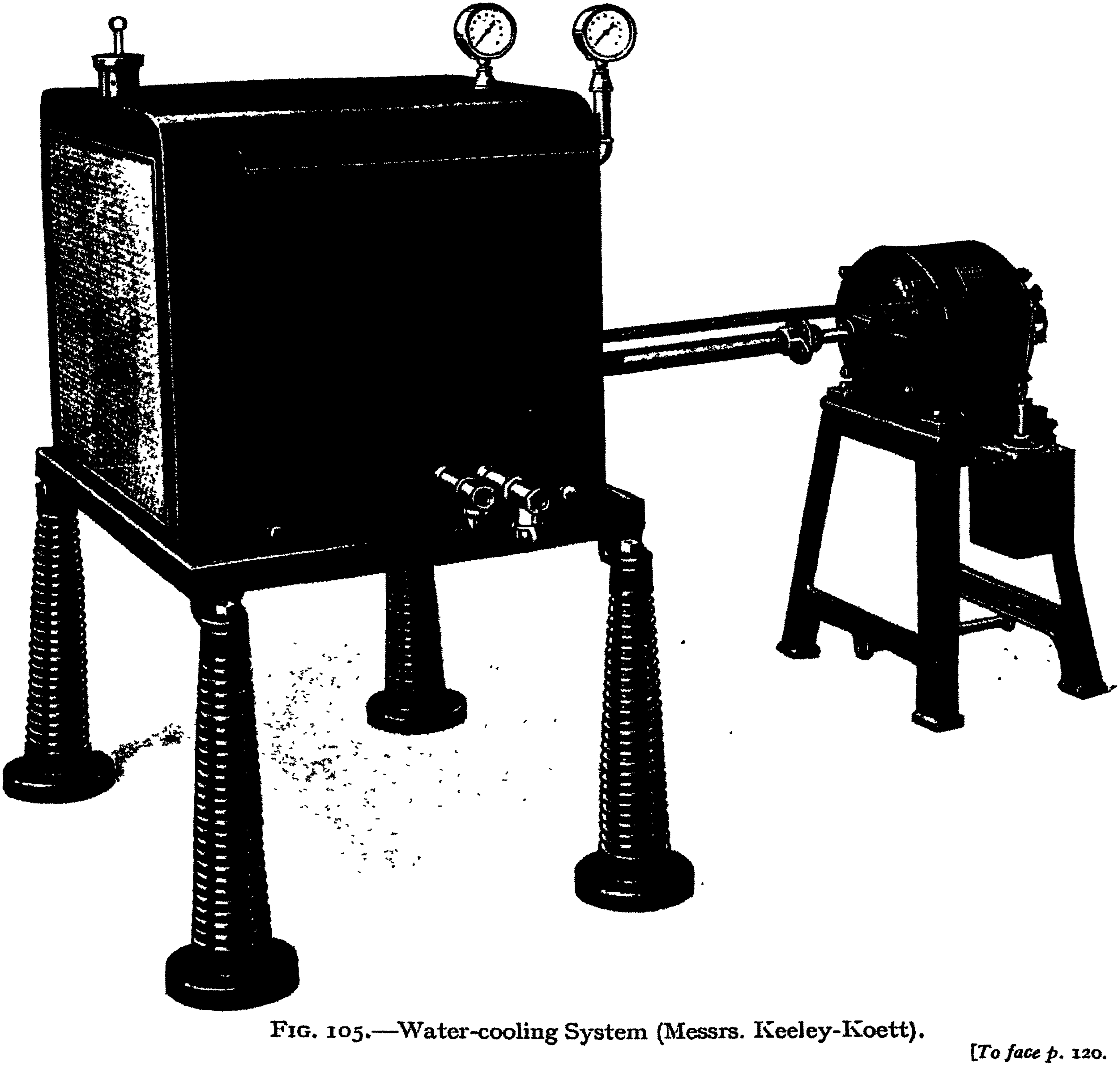


FIG. 105.—Water-cooling System (Messrs. Keeley-Koett).

[To face p. 120.

give the maximum cooling effect. The system has a safe cooling capacity for 50 milliamperes at 200 kv. tube operation.

A high-pressure flexible metal hose is used to carry the water to the X-ray tube and back again. A cleanable strainer, to collect any foreign matter before its entry to the X-ray tube ducts, is fitted. A directly connected rotary pump supplies the circulation pressure. The base casting of the cooling unit forms a pan to catch any overflow which may occur.

A still more elaborate cooling system has been elaborated by Morrison * of the Acme International Company under the title "water-oil-water" system. Another example of this system has been already mentioned (p. 118).

Morrison points out that large energy values of 10 kw. of heat energy have to be removed with modern tubes, and that such an energy value cannot be radiated into a treatment room, containing patients and operators, or if this is done and air cooling of the room has to be resorted to, very powerful electric fans have to be used.

Automobile radiators, he also states, are objectionable, as they are very subject to leakage, due to corrosion owing to acid formation by the nitric oxides formed by brush discharge from the sharp edges of the metal.

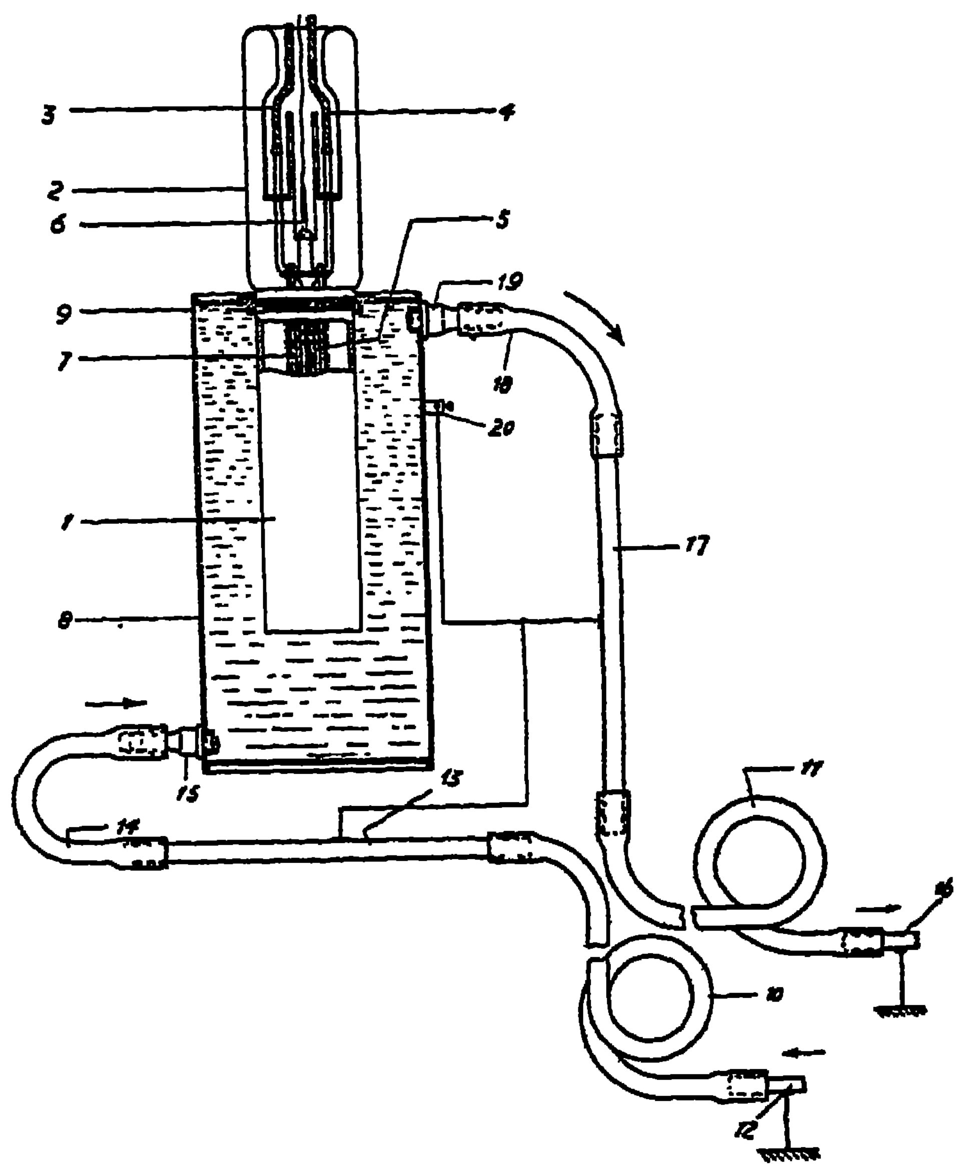


FIG. 106.—Philips Cooling System.

We may digress by stating that, in all such metal-cooling arrangements electrolytic action also tends to occur at all metal joints, since there is a fall of potential along the water path and, correspondingly, along the metal of the pipes enclosing the water. Due to differences in the resistances of the water and the metal pipes over the same length, local currents tend to be set up and particularly across joints. The resulting electrolysis of the joint metals then causes corrosion and destruction of the joints. Philips (Brit. Patent 235,892/1924) have suggested the use, in water-cooling systems, for example in a metallic valve or X-ray tube, of a mode of connection shown in Fig. 106, where lengths of metallic duct 15 and 17 are interposed between rubber connections 14 and 10 and 18 and

* *Bulletin of the Research Laboratory, The Acme International Company.*

11, where 8 is the water-cooling jacket of a metal valve or X-ray tube 1. If 15 and 17 are connected by a metallic conductor to 20, then 15 and 17 must have the same potential as 8. There is therefore no possibility of a current flowing over the joints 15 and 19, which are so preserved against corrosion, the action of which is transferred by this connection to the easily replaced ducts 15 and 17.

One may state that in general to avoid electrolysis at metal joints, due to stray currents, all metal parts should, if possible, be in metallic electrical connection.

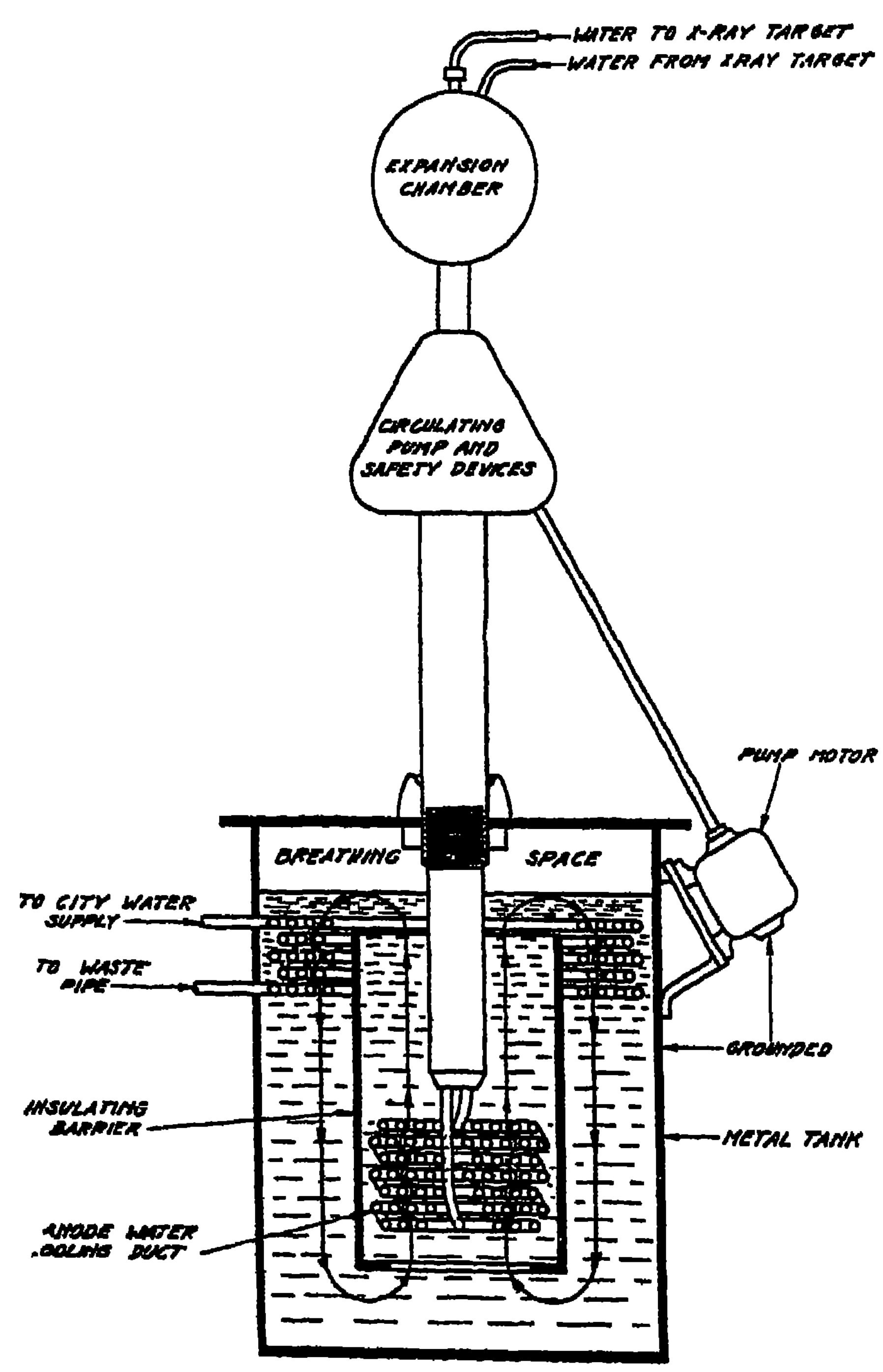



FIG. 107B.—Acme Company Oil-water-oil Cooling System.

Morrison states that if the water of such a cooling system should escape, it is not only very hot, but at a dangerous high electrical tension, and the patient's life should not be dependent upon the operation of some delicate relay as, if the water circulation ceases, the tube is practically instantaneously destroyed.

As the large heat energy must be carried outside the X-ray room, this prevents the use of a restricted quantity of water, as in the older systems of water cooling. Further the water must be chemically pure in such limited circulatory systems, or impurities will be deposited both mechanically and by electrolysis and so tend to block dangerously the ducts in the anode of the tube. To prevent such blockage the older water-cooling systems are fitted with strainers, *viâ* which the water passes.

A link should therefore be provided between the chemically pure water circulating in the anode and the copious normal supply of the district water system.

This is done by means of an intermediate oil-circulation. The actual apparatus is shown in Figs. 107A and 107B. The cooling system is all contained within a small grounded metal tank and has no parts by which shock may be caused to the operator or patient, except the connection to the high-tension system, which should be out of reach. The water is circulated in the tube by means of an insulated motor pump and the heated water passes to a series of cooling ducts in oil. These are

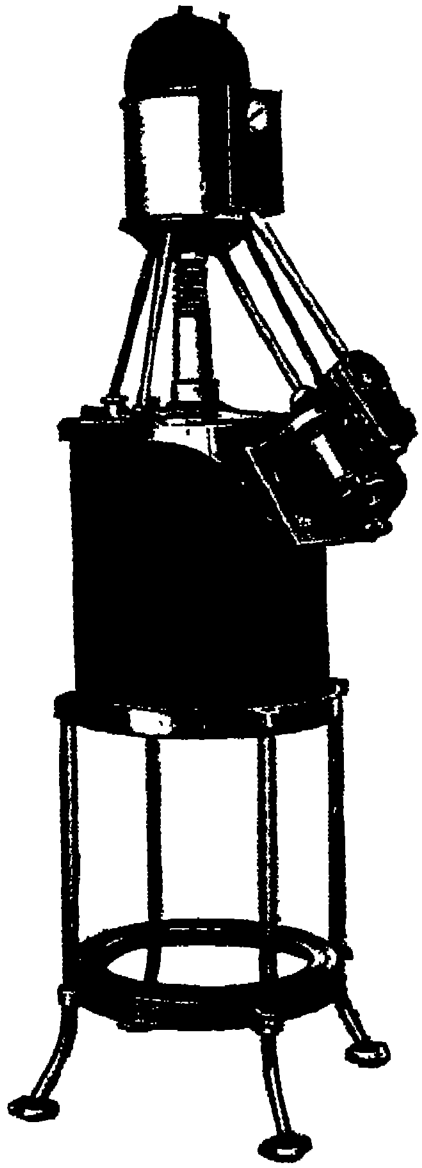


FIG. 107A.—Acme Company Oil-water-oil Cooling System.

[To face p.

surrounded by an insulating barrier, outside which are the normal water mains of the town water supply.

The latter are arranged at the top of the tank, so that the heated oil, in turn heated by the circulation of water within the anode duct system, must rise to the surface by convection and circulate around the coils carrying the outer water supply.

In the pump housing there are safety devices which do not depend upon water pressure, since, if the circulation of water stops, this pressure must necessarily rise. Any device which merely requires a certain pressure of water, before it can operate, is therefore useless to operate the low-tension transformer circuit for the purpose of safety, when the circulation within the anode is interrupted.

The protective devices are therefore operated more safely by the effects of any rise of temperature which must occur should the anode circulation be choked.

Morrison points out that the energy passing *viâ* the tube can be very simply measured if the ingoing and outgoing temperatures of the water are known and the mass of water circulating per unit time. Since the ratio of X-radiation to heat energy varies between $\frac{1}{1000}$ to $\frac{1}{10000}$ and the light energy is nearly equally negligible, the heat energy is approximately that passing *viâ* the X-ray tube, and, assuming a constant relation of X-radiation and heat energy, is a rough measure of the X-ray energy emitted by the tube.

The system described is designed for use in connection with the large tube holder described in Chapter VIII., Vol. II. The tubes used are the larger Coolidge tubes, in which the cooling water flows in anode ducts (Fig. 100). As already mentioned, the use of efficient cooling devices is imperative in these 250-kv. 50-milliampere tubes since, if the temperature gradient exceeds certain limits, there is great risk of the metal cracking and water entering the tube vacuum with dangerous results.

The cooling of the anode by air circulation (Fig. 108) has already been mentioned, but is little used, as it is by no means as effective as water circulation.

It has occurred to the present writer that the cooling of the anode could be greatly facilitated by the use of adiabatic expansion and cooling of gases, when allowed to escape from a high to a low pressure. It is well known that if a gas is allowed to evaporate from the solid or the liquid state at high pressure and only allowed to escape *viâ* a small jet, then, since the gas must obtain the energy of expansion from its own intrinsic kinetic energy, its temperature is greatly lowered.

This effect has been utilised in the well-known Linde refrigerating apparatus and used by K. Onnes to obtain the very lowest temperatures approaching absolute zero, at which all gases are liquid or solid. The cooling by adiabatic expansion is progressively increased by allowing the

escaping cooled gas to circulate around the spiralar oncoming gas pipes. Such a theoretical arrangement, applied to an X-ray anode for cooling purposes, is shown in Fig. 109, and it would be necessary to arrange for the escaping gas to obtain exit to the external air, particularly if easily obtainable carbon dioxide snow were used. The cooling effect would be most intense, and it would be very necessary to proportion the target

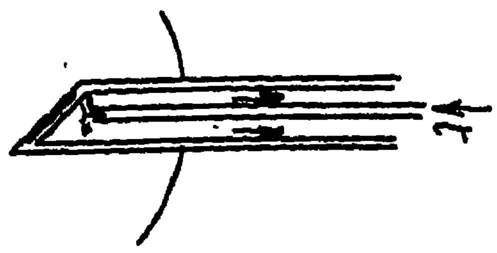


FIG. 108.

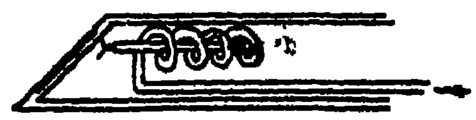


FIG. 109.

suitably to avoid too great a temperature gradient across a given distance of metal, or rupture of the material might result.

With such a method of cooling and the use of a self-rectifying electron tube, it should be possible to obtain tubes which would be self-rectifying at much higher loads than those at present possible, *i.e.*, 30 milliamperes at about 60 kv.

This method of cooling does not appear to have been utilised in commercial X-ray apparatus, doubtless on account of the greater complexity of operation involved.

## PRACTICAL OPERATION OF X-RAY IONIC TUBES

The ionic, or gas tube, suffers in operation from the fact that it is impossible to vary the applied potential and resulting quality of radiation, without a corresponding variation of the current *viâ* the tube and intensity of radiation. In the electron tube it is possible to maintain either the potential or the current constant whilst the other is varied.

Further in the ionic tube the current *viâ* the tube can only be varied by some type of softening device and if over-softened, a good tube may be rendered temporarily, or permanently, useless.

For this reason more skill is required for gas-tube operation, but this is by no means difficult. Too much stress is very often laid by the older radiologists upon the degree of skill necessary for gas-tube operation, and in fact, the operation of gas tubes can equally suffer from an excess of skill on the part of the operator, *i.e.*, overdue interference. It is quite possible to screen and take some hundreds of thorax plates with a good gas tube with only very few failures, without the tube being in any way interfered with, and this is the case at one of the writer's hospitals. Were such a tube repeatedly softened this would not be possible.

It is often stated a battery of gas tubes should be kept of varying degrees of softness or hardness for different purposes. It is admitted for

radiographic purposes two or three tubes are useful, for example, a soft tube, a hard tube and one or more tubes as stand-by or resting tubes.

Where however much work has to be done, such an interchange of tubes, entailing in practice often the loss of ten minutes in the modern totally enclosed tube box, is really impracticable, and equally good results will be obtained with a single tube, worked at different potentials according to requirements, with adjustment of time of exposure, to correct for the current variation.

In a small hospital it is not a sound proposition to keep a battery of six or more tubes, costing about £10 each, for the amount of work to be carried out, although the extent of work more readily allows their repeated interchange. The present writer's advice is that, having got a tube which gives good results, to leave it severely alone until it shows some defect, usually of hardness, when a judicious softening is all that is required.

Any radiologist who is unable to obtain the little skill required for gas-tube operation is better advised to change to the more easily operated, but much more expensive, electron tube.

Much has been written as to the relative merits of the gas tube over the electron tube and *vice versâ*. Equally good results can be obtained with either, if their operation is correctly appreciated. The author has used both. The only reason for the preference of the gas tube is on the score of cost.

In all such discussions of superiority it should be, but is hardly ever, recollected that the tube is not the only variable factor in radiography but that equally important variations occur in the patient's size and X-radiation absorption and in development and fixation of negatives. A correctly exposed plate is quite likely to be spoilt by a practically unavoidable error in development or fixation. Further, in the author's experience, some very spare patients seem to have a remarkably greater density than other patients and, for this reason, are equally as difficult to radiograph as a much stouter patient.

The average clinical physician or surgeon never appears to appreciate the number of variables in the operation of obtaining radiographs. With the same operator upon the same apparatus, at the same attendance, the majority of the plates will possibly be of good quality, whereas a few will be most excellent and a few poor. Clinicians will often be met who claim to tell plates taken by two operators with the same apparatus and conditions, but, failing definite marking, such a claim is open to disproof. The author well remembers such a case where a clinician affirmed a poor plate had been taken by one operator and a good plate by another operator, but such a claim fell to the ground when it was found both the good and the bad plate had been taken by the *same* operator.

The greatest asset with such critics is when they themselves purchase

an installation of the type " you turn the handle we do the rest," and then begin to perceive the practical difficulties of radiography, owing to the numerous variables, which are not merely those of current and voltage, as assumed with such apparatuses, but equally a question of the size and psychology of the average patient.

In the operation of gas tubes a few desiderata hold. If circumstances permit, an X-ray tube of any type should not be placed too near any highly inductive apparatus as an X-ray induction coil, or transformer, and particularly the former. The strong magnetic fields of such apparatuses may result in the cathode stream of the X-ray tube being deviated, with resultant variation both of hardness, *i.e.*, the potential necessary to drive electrons from cathode to anode, and of focus, due to the cathode stream being incident on a different region of the target or, even upon the copper of the anode head, with resulting fusion of this. When it is remembered that a magnetic field is used to deflect the cathode stream in the classical Thomson determination of the ratio $\frac{e}{m}$, the effect of variations of magnetic or electrostatic fields in practice will be obvious.

Theoretically, to avoid electrostatic variations, the leads of an X-ray tube should be preferably brought to the tube directly horizontally or, if, as usual, this is not practicable, directly downwards. This is often not possible in practice and likewise it may be imperative in a small room to have tube and voltage exciting apparatus close to each other.

A further source of irregularity of an X-ray tube may arise if it is located near to a constantly sparking protective spark gap. It should be remembered that such gaps give rise to ultra-violet and even soft X-radiation which, falling upon the thin wall tube, may either penetrate the tube and cause variation of operation, or, by altering the ionisation of the surrounding atmosphere and the tube walls, likewise give rise to irregularity. Conversely the X-ray tube radiation interferes with the gap operation even if this is of the sphere-gap type.

When a tube is clipped into the usual tube supports of an X-ray tube box, which are far from ideal (see Chapter VIII.), the firmness of the supports' grip should be sufficient to hold securely the tube into position, but not too great, as during extended use the glass will heat and expand and fracture may result from a too tightly fastened clip. The tube must be correctly centred with respect to the diaphragm.

In the ionic tube various defects may be present, the chief of which are ;—

(1) The tube is erratic, but not useless.
(2) The tube is too soft.
(3) The tube is too hard.
(4) The tube is incorrectly connected.
(5) The tube is " punctured."

(6) The tube is " cranky " and useless, owing to bad workmanship or evacuation.

With new tubes a wide variation of the hardness and resulting current will often be found. This is due to the tube having been insufficiently operated during exhaustion before sealing off. As a result the tube target, on becoming heated by use, gives off occluded gases and so renders the tube soft. To remedy such a defect the tube may be deliberately overloaded. The excessive current will then cause the heating and release of the occluded gas. Usually, the gas having so been practically entirely occluded, the tube will become more steady during operation and whilst soft, on cooling, the excess gas may be more evenly re-occluded by the metal electrodes and the tube walls, so that during future use there is less gas in the target itself to render the operation erratic in action.

If, as is quite possible, the resulting softness is not too great, such a stabilised tube may be gradually hardened by using it for superficial treatment work, it being well-known a tube hardens with continued use.

An alternative method is to use the tube with an aluminium filter to cut off the unusefully soft radiation and to use a greater voltage (and current) than normal, which may soon cause it to harden, but may have a converse effect.

It is often stated that, if a tube becomes too soft due to the above deliberate or any other procedure, there is no recourse but to send it back to the makers for re-exhaustion. This return, unless the tube is new and better exchanged directly for a suitable tube, can often be obviated if the tube is operated in reverse connection with intervening periods of rest. Such a procedure must be carefully carried out, as the cathode now acts as target and gives unuseful soft radiation, which is directed upon the glass bulb usually below and behind the target. The glass in consequence becomes unduly heated in this region and, if the reverse excitation is continued for very long, may puncture.

The effect of such deliberate reverse operation causes the target to " sputter." The small sputtered particles are then distributed throughout the tube, but chiefly upon the walls. On the lapse of some little time, this sputtered metal adsorbs gas by occlusion and so lowers the pressure, rendering the tube hard.

A soft and unsteady tube may often run hard and steady if the anticathode-anode connection is removed (see p. 99).

With regard to the re-exhaustion often stated to be necessary when used tubes are returned to the makers, it may be stated that a tube is rarely re-exhausted. To do so involves that the tube is punctured by heating a small region, to which has to be fused an exhaustion tube. This operation is, in an old tube, a very delicate one, and should fracture occur, as is very likely, there is some considerable danger to the glass blower due to implosion. Since a new bulb (chiefly of Dutch origin in

England) only costs 3*s*. or 4*s*., it is cheaper and much more safe to break the old bulb under safe conditions and remake the electrodes in a new bulb.

In consequence the cost of repair usually approaches that of a new tube and, unlike the purchase of a new tube, there is no guarantee upon the part of the manufacturer as to its future work. The author's own experience with such remade tubes is that they are invariably " cranky " and unsatisfactory and it is a more safe proposition to buy a new tube, when £6 to £7 is often asked for reconstruction, than to continue with a remade tube the target of which is very likely much worn. It is very hard to scrap a tube which has given long and good service, but it is very likely that, if remade, it will have lost its original excellent properties.

A scrapped tube only has value as regards the nature of the target. If this is platinum it may have an intrinsic value of several pounds but, in modern tubes, it is usually of tungsten, and the intrinsic value is based upon the fact that tungsten is valued at only a few pounds per pound weight, *i.e.*, the tungsten target is only worth a very few shillings as scrap metal.

In view of this and the fact that a suitable exhaustion plant can, and often is, installed in a small back room, and that a single glass blower can manufacture many tubes per week, the ruling prices of gas tubes from £10 upwards would appear to be excessive.

Tubes submitted for repair are usually reported as " well worth repair," and it is of interest to then ask whether the manufacturer will purchase it, if this is the case.

A tube which is operated upon a coil installation in which there is much inverse current will have its anticathode sputtered and so become hard owing to resulting gaseous occlusion. Use upon such a coil will equally tend to harden a very soft tube until it becomes suitable for more general use.

Whilst such inverse current, which is necessarily present with an induction-coil discharge, can be practically cut out by the use of valve tubes, the necessity of controlling the operation and hardness of such valve tubes, in addition to the X-ray tube itself, often renders it more convenient to neglect this effect in an X-ray tube to its detriment and shorter life, rather than incur the expense and nuisance of valve tubes.

In this connection the apparent hardness of a perfectly good X-ray tube will often be traced to a hard valve tube also in circuit and, it should be recollected, valve tubes require regulation of their hardness equally with the X-ray tube. Such valve tubes also greatly reduce the potential across the X-ray tube itself owing to their very high resistance, if of the ionic type. The advisability of use of a large induction coil with many valve tubes, to cut down the heavy inverse current, is discussed elsewhere (p. 280).

A tube which will work satisfactory in the open will often work badly when enclosed in the modern type of tube box. This subject is

also discussed in detail elsewhere (Chapter VIII.), and is largely due to energy being lost by leakage and other electrostatic losses *viâ* the box, so that less energy actually passes *viâ* the tube itself and the tube therefore appears soft owing to the increased total current, if softness is merely judged by current value rather than spectrometrically.

It is obvious to compensate for these losses a greater potential must be applied when the tube is enclosed, for the same current to pass actually *viâ* the tube.

A tube which has become very hard with extended use and which can no longer be regulated by the particular regulating device fitted,* can often be softened by heating it in a sand bath, or oven, so causing the occluded gas to be given off. Such a method of softening has usually only a temporary effect, as the gas is quickly re-absorbed on again cooling. A much more permanent result is likely to be obtained if the tube is deliberately overloaded with a heavy current *viâ* the tube, in the hopes that any gas which may be occluded in the electrodes will be disengaged, and render the tube soft. Naturally the end result may only be to badly pit the target, instead of the result desired.

When a tube punctures the increase of pressure to atmospheric is not usually immediate and the discharge takes the form of the blue glow of a partially evacuated vessel where, whilst the pressure is too high to allow the electrons to obtain, between molecular collisions, a sufficient energy to excite X-radiation and resultant green fluorescence of the glass, the pressure is low enough for them to excite colour effects in the gas itself. A puncture is often very hard to find and a method is given in Chapter I. Such punctures, if found, usually consist of a funnel-shaped hole.

A large puncture results in total suppression of the current *viâ* the tube and no coloured effects. The remedy for a punctured tube is only in the hands of the glass blower.

Incorrect connection of an X-ray tube is indicated by the absence of the usual hemispherical green (or other colour) fluorescence, a patchy ringed appearance with a bright spot opposite the anticathode and blue tinges in the bulb. The physical explanation of the coloration is to be sought in the fact that the ions have now not sufficient mass and energy to excite the normal green fluorescence, characteristic of the greater energy ions normally obtained.

This soft radiation will be focussed upon the bulb behind and usually below, the target and, as already mentioned, is by its great absorption and heating effect very liable to cause fracture, particularly since the glass joint of the bulb and anticathode sleeve is in this region.

Reverse connection and resultant fracture is a very potent source of tube failure. If the tube is unseen (by enclosure in a tube box) no

* In this respect the Bauer regulator (*q.v.*), by which gas can always and indefinitely be admitted to the tube, has obvious advantages.

reading of a single-reading milliamperemeter or a reverse reading of a double-reading milliamperemeter should lead at once to inspection of the connections of the tube for this cause.

A few new tubes of a considerable number will be found unstable and erratic and are usually termed "cranky." Such defects are due to faulty manufacture, *i.e.*, the use of non-gas-free metal for the electrodes, incorrect centring of the electrodes, insufficient heating and operation during exhaustion.

Such tubes are useless and, after a preliminary trial to see if they will settle down, they should be returned to the tube-maker.

There are no recognised tests for the selection of X-ray tubes but the following are suggested ;

(1) The target should be mirror-like, unpitted and uncracked.

(2) On use the focus of the cathode is in the centre, or near to the centre, of the target. Most tubes do not give such a focus exactly, owing to the great mechanical difficulties of exact centring of cathode and anticathode during construction, and a reasonable degree of latitude can be allowed, but too great a deviation will result in nearly total loss of focus of the emitted X-radiation.

(3) The cathode should not be unduly darkened. The black or iridescent rings, produced by tube operation during exhaustion or trial, should be symmetrically around the cathode centre.

(4) None of the visible effects of puncture to be present during operation.

(5) The voltage, in terms of a given spark gap, which will break down the tube resistance should be correct and the discharge does not fluctuate.

(6) The specified current for screening purpose remains steady after five minutes operation without change of vacuum or hardness.

(7) The specified current for radiography is maintained steadily for 30 seconds, without change of vacuum (or hardness).

(8) The tube will pass double the specified radiographic current for 15 seconds without change of vacuum, this being a test of the freedom from gas of the electrodes.

(9) The focus is fine, medium or broad as desired. This may be tested by radiography of metal gauze, placed at given distances from the tube focus and the photographic plate. A sharp focussed tube should give a sharp image of the gauze, whereas a broad focus tube will tend to give a general blackening of the photographic plate with no sharp gauze image, owing to the effect of optical "penumbra." An analogous method is used in the Christen penetrometer (p. 174, Vol. II.). As there are no exact definitions of fine, medium and broad focus tubes the distances, target to gauze and gauze to photographic plate, must be selected by the particular experimenter. Details of foci diameters of fine, medium and broad focus Coolidge tubes will be found in Appendix II., p. 534.

(10) The workmanship is good, *i.e.*, electrodes, terminal caps, etc., do not rattle on shaking, or are not loose. The bulb should not be too small in volume, or the vacuum is then more liable to variation.

## EXERCISES ON CHAPTER II.

*Questions* 1 *to* 3 *are based upon analogous questions set in the D.M.R.E. Examinations of Cambridge.*

(1) Give a diagram to show the distribution of X-ray energy radiated by an X-ray tube target. How would you measure the minimum wavelength emitted and what is its practical importance ?

(2) What is meant by the " focal spot " of an X-ray tube ? Discuss the factors which operate to produce a focus in both the gas and the electron tube. How does a light and a cathode ray focus differ ?

(3) Give the relation of heat production to current in an electrical circuit. An X-ray tube passes 4 milliamperes at 120 kv. Calculate the heat production per minute, assuming all the energy appears as heat only. How is this energy removed in practice ?

(4) Describe a modern X-ray tube used for X-ray therapy. (Soc. of Rad. Exam., December, 1922.)

(5) In a prolonged treatment when using an ordinary gas tube, what steps would you take to maintain a constant vacuum ? (Soc. of Rad. Exam., June, 1925, and June, 1926.)

(6) Describe all the methods of regulating the vacuum of gas tubes. (Soc. of Rad. Exam., June, 1926.)

(7) Describe three methods of regulating the vacuum of a gas tube. (Soc. of Rad. Exam., December, 1925.)

(8) What are the main essentials required in a metal of the target of an X-ray tube ? How does the X-ray output depend on the material of the target, the exciting voltage, and the current through the tube ? (Soc. of Rad. Exam., June, 1926, and December, 1925.)

(9) Describe the various glasses used in the manufacture of X-ray tubes.

(10) Give diagrams to show the variation of charge upon the envelope of (*a*) a gas tube, (*b*) an electron tube.

(11) What is the action of the anode or third electrode of a gas tube ?

(12) Describe the automatic regulation of a gas tube by the osmosis method.

(13) Compare the condenser, osmosis and Bauer valve methods of softening X-ray tubes.

(14) Describe the cathode of a gas tube. What is the effect of withdrawing it into the cathode neck of the bulb ?

(15) What are the functions of a target hood in an X-ray tube ?

(16) Explain how X-ray tubes may be cooled by (*a*) radiation, (*b*) conduction, (*c*) convection of heat.

(17) Give particulars of a cooling system for high-power X-ray tubes.

(18) Describe how the electrostatic stress over the glass envelope of an X-ray tube may be minimised.

# CHAPTER III

## THE X-RAY TUBE—*continued.*

## THE ELECTRON TUBE. THE METAL TUBE. ACCESSORY ELECTRODE TUBES. VALVE TUBES

### THE DEVELOPMENT OF ELECTRON TUBES

THE development of the electron tube is later than that of the ionic tube, over which it undoubtedly has the following advantages ;—

(1) More easy regulation.

(2) More regular operation.

(3) It is very suitable for very heavy loads, or long-continued operation at smaller loads, as there is no variation of the degree of vacuum, as with the gas tube.

(4) For certain purposes, such as X-ray cinematography, with a constant potential source of energy, the discharge is continuous, with resulting advantages for such purposes. With the ionic tube, even with a constant potential source of energy, the discharge is discontinuous and, in such cinematographic work, difficulties arise owing to the lack of synchronism between exposure and maximum current *viâ* the tube.

(5) Since no accessory anode is necessary the overall dimensions of the tube are smaller. This allows the tube to be surrounded by a protective box, or shield, of smaller dimensions. The weight of protection is thereby much reduced and, in turn, the necessary counterweights and mechanical arrangements. A comparison of American and English apparatus as shown elsewhere in this volume will render this advantage most evident.

(6) In the smaller electron tubes, quite sufficient for most diagnostic purposes, the tube is self-rectifying for loads which do not render the anode incandescent. Rectifiers and interrupters are therefore unnecessary, with consequent economy of apparatus and space, of particular importance in portable apparatus.

The weak point of the electron tube is the fragility of the incandescent filament under the great electrostatic attraction resulting from the high potential between cathode and anode. Methods are however described later by which the effect of this attraction can be overcome.

Perhaps the greatest advantage of the ionic tube over the electron tube is on the score of expense and it is the high cost of electron tubes which have delayed their more extensive use.

As with most scientific apparatus, the development of the electron

tube has been a gradual development and occurred simultaneously in various countries.

Whereas, in England, the term electron tube is nearly synonymous with Coolidge tube, abroad, the electron tube of Lilienfeld has been very extensively used. Furstenau has also claimed priority in the production of electron tubes and in Germany the Furstenau-Siemens tube, practically identical with the Coolidge tube, has been much employed.

By the term electron tube we may denote a tube in which the source of electrons, which constitute the current, is obtained by use of a heated thermionic filament and the degree of vacua is usually so great that gas ionisation plays no important part.

The development of such tubes was therefore dependent upon the practical obtainance of the necessary degree of vacuum, in order to remove the disturbing effects of gas ionisation, which complicate the thermionic emission.

This production of high vacuum has been very largely due to the fundamental work of Gaede and his various pumps, and the measurement of such vacua to Knudsen.

Equally the subject of thermionic emission, first discovered by Edison in 1884 (Edison Effect), was first placed upon a scientific basis by the fundamental work of the Englishman, O. W. Richardson.

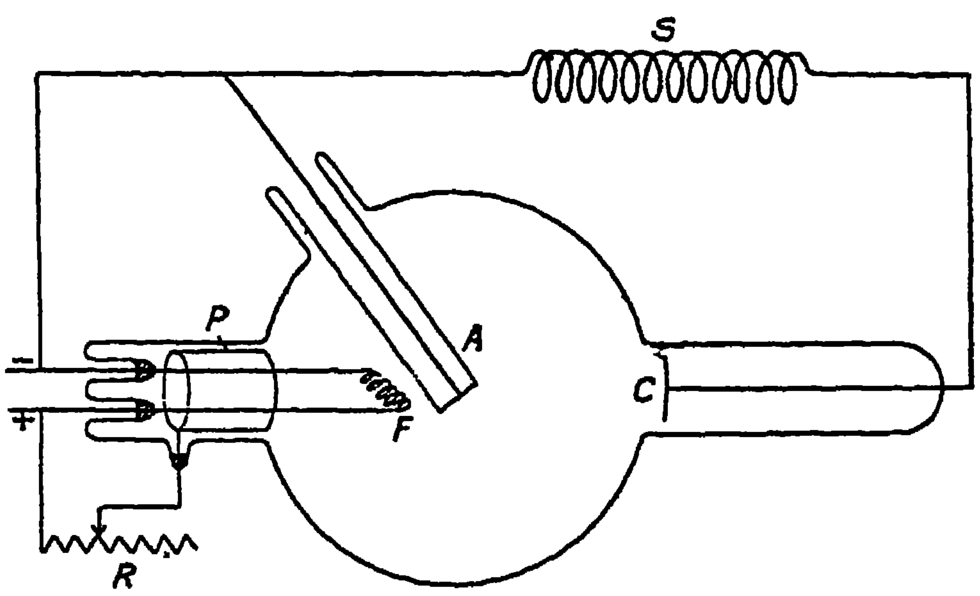


FIG. 110.—Original Lilienfeld Electron Tube.

The use of a filament in an X-ray tube is a very old one, such filaments being first introduced by Gover and Cooke (Brit. Patent 31,109/1897) in 1897, who used a carbon filament, and independently by Bonetti in 1898* who used a platinum filament, both very soon after the discovery of X-radiation in 1895 and prior to the first knowledge of the electron. Morton, in America, also employed such a filament.

It is difficult to judge how great a part in electron emission such filaments played, since whilst they were introduced in order to soften the X-ray gas tube, as well as to give off occluded gas when heated, they must undoubtedly have also caused softening by thermionic emission.

Wehnelt,† Wehnelt and Westphal, in 1904, and also Dember, and in England Whiddington ‡ (in 1912) used for X-ray tubes Wehnelt cathodes, *i.e.*, incandescent cathodes coated with alkaline earth deposits.

* *Comptes Rendus*, 126, p. 1893, 1898.
† *Ann. der Phy.*, 14, p. 425, 1904. *Bericht der phy. med. Ges. Erlangen*, 37, p. 312, 1905.
‡ *Proc. Camb. Phil. Soc.*, 17, p. 144, 1912.

Lilienfeld in 1910,* appears to be the first to have introduced an electrically heated platinum filament, or strip, in order to render discharge possible *viâ* an X-ray tube so highly exhausted that discharge was otherwise impossible. The form of tube used, as shown by Dauvillier † (Fig. 110), is essentially that of the modern electron tube of the three-electrode type except an alkaline oxide (or Wehnelt) cathode was used in place of a tungsten filament.

Furstenau in 1912 (German Patent 271,306/1912), similarly used a heated filament to promote discharge in a highly evacuated X-ray tube, otherwise incapable of discharge, and the patent of Furstenau was held by the German courts as fundamental in respect of electronic X-ray tubes.

In England the only electron tube known is that of Coolidge, since radiologists have hesitated to introduce the Continental electron tubes of Lilienfeld, Furstenau, Müller and others, owing to the great risk of litigation in connection with such use.

This tube, of the American General Electric Company, has been produced as the result of the work of two physicists of this company, namely Langmuir, who first studied the Richardson Laws of thermionic emission as shown by tungsten filaments in highly evacuated space, and Coolidge, to whom is due the practical methods of production of pure tungsten, free from gas, and the construction of a practical X-ray tube.

Considerable discussion has occurred between Langmuir and Coolidge upon one part and Lilienfeld on the other part as to priority as regards the electron X-ray tube, which will be found in the *Physical Review* of 1913 and 1914.

From this discussion it appears to the author that there can be no question that Lilienfeld's earlier experiments were conducted with what was essentially an electronic tube, *i.e.*, a tube in which, owing to the high degree of vacuum, a discharge was impossible except by use of thermionic emission from heated platinum, coated with alkaline earth oxides.

Lilienfeld appears however to have incorrectly ascribed the action of the tube to ionisation of the minute residual gas and, in consequence, to have obtained results for the laws regarding thermionic emission which are not in accord with the laws of thermionic emission now generally held and which his later results ‡ appear to show were dependent upon other factors than gas pressure and not, as claimed by Langmuir, insufficient exhaustion, as there is no doubt Lilienfeld utilised in his earliest tubes the highest degree of vacuum obtainable.

The first English patent with respect to electron tubes is that of Lilienfeld (Brit. Patent 23,169/1912, dated October 10th, 1911), in which he used a heated platinum film in order to promote electron emission to

* *Ann. der Phys.*, 32, p. 673, 1910. *Fort auf dem Geb. d. Rönt.*, 18, p. 256, 1912.
† Dauvillier, "La Technique des Rayons X," p. 47.
‡ *Ann. der. Phys.*, 61, p. 221, 1920.

cause discharge between independent anode and cathode electrodes. It is stated: "The hardness of the rays generated in a tube, *exhausted to a high degree of vacuum*, is adjusted by passing a low-pressure exciting discharge of graduated intensity from an auxiliary cathode, which consists of platinum coated with metallic oxides and is heated to incandescence by a constant current. This discharge may pass to an auxiliary anode arranged in a side chamber or placed between the main electrodes, or it may pass to the anticathode. The auxiliary cathode is preferably connected to the main anode or anticathode."

In a further patent (Brit. Patent 1843, January 22nd, 1913), Lilienfeld rearranges the electrodes in the order of their maximum potential, as in the modern Lilienfeld tube.

The fundamental Coolidge patent is that of the General Electric Company of America (Brit. Patent 14,892, June 27th, 1913), for what is essentially the modern Coolidge tube, which, besides difference as regards number and arrangement of electrodes, differs from the tube of Lilienfeld by the employment of a tungsten filament, instead of a Wehnelt coated cathode as used by Lilienfeld.

Whilst the exact origin of the electron tube is a matter of dispute, there can be no question that the cost of such tubes, ranging from £40 to £180 each, is grossly excessive, particularly since the manufacture is essentially not much more costly than similar ionic tubes, which are already sufficiently expensive. Further, after installation, the cost of repairs of such electron tubes is usually threefold or fourfold, that of ionic tube repairs and attempts have been made to restrict their repair by ionic tube manufacturers, equally capable of doing such repair, since the necessary pumping plant is simple and not costly.

In view of the ruling cost of electron tubes the full development of the electron tube is only to be expected now that the earlier patents are about to expire, when unquestionably their more generalised manufacture must result in further improvements in such tubes.

Meanwhile the author, when advising with respect to new installations, makes it a practice to advise provision of the necessary aerials and switches for electron-tube operation, but to await the production of cheaper electron tubes with lower costs of maintenance repairs.

The more recent introduction of a practical metallic electron tube with non-ionising gas filling, having all the advantages of the highly exhausted electron tube, is proving a serious competitor to the earlier type of tube but, unfortunately for the practical radiologist, no attempt has been made in the direction of reduction of their high cost.

Further competition, to the benefit of the radiologist, is to be expected in the form of the auto-electronic, non-filamentary, high-vacuum electron tube, should this tube receive the development it appears to merit.

## CONSTRUCTION OF ELECTRONIC TUBES

We have, in Chapter VI., Vol. I., sufficiently developed the theory of thermionic emission for the purposes of the medical radiologist.

In the electron X-ray tube we have a filament which, being heated, causes the emission of electrons the passage of which constitutes the current *viâ* the tube. These electrons, emitted with low velocities, being within the electrostatic field between cathode and anode (target) are rapidly accelerated by the field towards the anode.

The speeds they obtain are dependent upon the electrostatic field and therefore potential between the cathode and anode. These speeds in turn determine their kinetic energies.

By their arrest at the anode, their kinetic energy is radiated, largely as heat and light energy, but also as ultra-violet and X-radiation energy.

The filament is invariably of tungsten, but other metals are available. A typical Coolidge-tube filament is a tungsten spiral of ·2 mm. diameter of about half a dozen turns, within a circle of 3·5 mm. diameter. To give a focussing effect, this spiral is inserted within a hood of tungsten or molybdenum B with a shield of similar metal (Fig. 111). The charge upon this hood and shield causes a repulsion of electrons except in the direction of the tube target and so gives the effect of a focus. The shield also serves to prevent the emission of electrons from the filament in a backward direction and, more importantly, serves to distribute the electrostatic stress, so that this is not concentrated upon the mechanically weak filament, the form of which, by attraction towards the anode, tends to be distorted.

The "focus" of the electron beam upon the target is dependent upon the relative positions of filament, hood and shield, the placing of the filament towards the hood mouth tending to give a broad focus, by decreasing the electrostatic repulsion and *vice versâ*.

A further advantage of the cathode hood and shield, invariably present in all Coolidge type tubes, is that it serves to protect the delicate filament from electronic bombardment, should inverse current pass *viâ* the tube, when this is used with either the induction coil or transformer, without some form of rectifier. When, as is often the case with the heavier tubes, only designed for use with a rectified voltage, the target becomes white-hot, the heated anode target is a greater source of electrons than the filament. Under the influence of any reversely directed potential, the electrons emitted from the target would bombard and rapidly destroy the delicate filament, were it not that the bulk of the reversed electronic current flows to the hood and shield rather than the filament.

The filament is not all at the same temperature, *i.e.*, isothermal, since it is fused to molybdenum supports. It is well-known that at such joints differences of potential result, due to thermo-electric (not thermionic) action, and, in consequence, the filament is not isothermal.


(1) (2)

FIG. 111.—Electron Tube Cathode.

[*To face p.* 136.

Tungsten has a high melting point (3,267° C.) and allows very intense heating, but such a filament will not permit the passage of a current greater than 4·5 amperes without resulting disintegration. The normal life of such a filament is about 2,000 hours, by which time its diameter is reduced by 10 per cent., owing to disintegration.

Dauvillier has stated that at 2·530° K. (absolute) such a filament is capable of giving electrons sufficient to allow the passage of 80 milliamperes per square centimetre, or in all 500 milliamperes, for the normal Coolidge

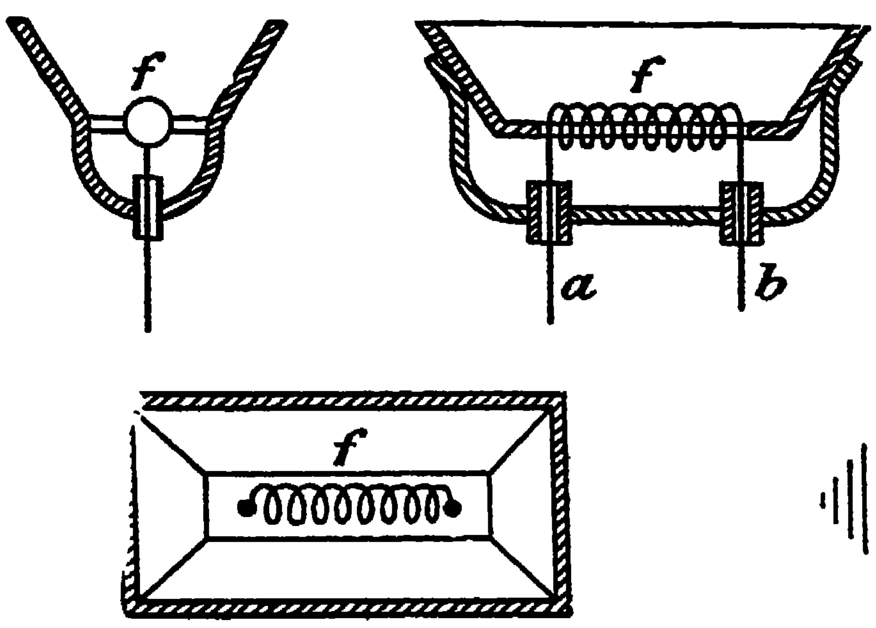



FIG. 112A.—Müller Line Focus Cathode (Original Form).

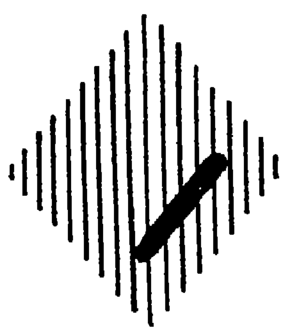


FIG. 112B.

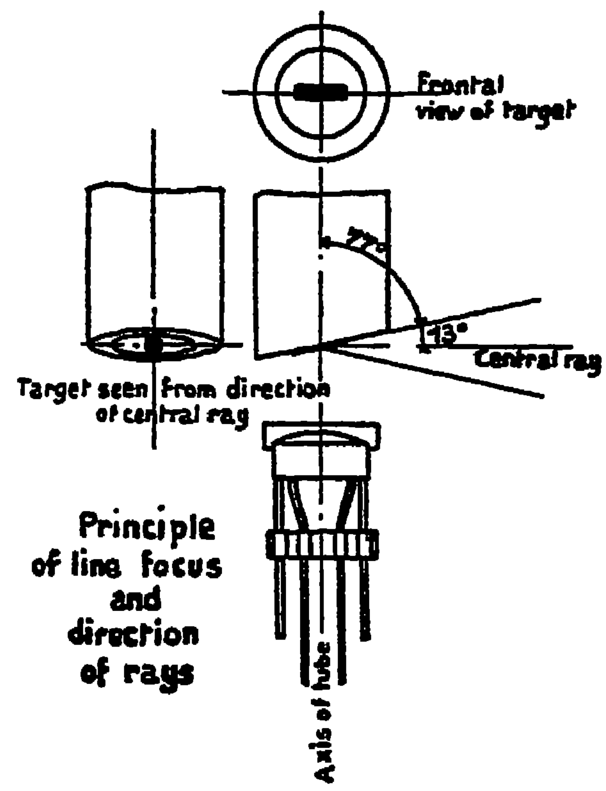



FIG. 113.

filament, the effect of the thermo-electric variations at the joints being neglected.

Müller (Brit. Patent 200,773/1923), in order to obtain a line focus tube uses a filament longitudinally and symmetrically situated in a shield of rectangular form in the plane perpendicular to the target and of triangular section as regards its depth (Fig. 112). The focus of such a filament upon the target is a line, but in perspective is a point (Fig. 113) (Goetze).

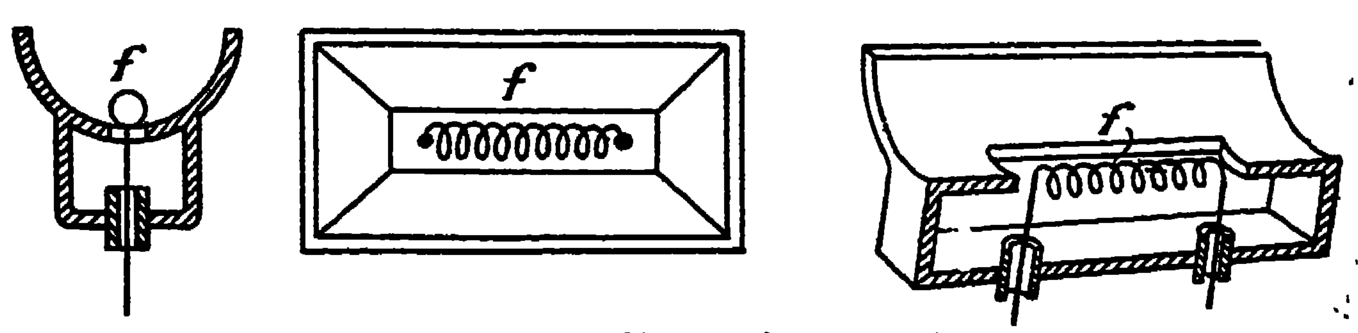



FIG. 114A.—Müller Line Focus Cathode (Modern Form).

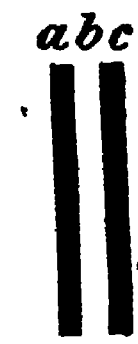



FIG. 114B.

Whereas a point focus upon the target would lead to local excess temperature and pitting of the target, a line focus, by more evenly distributing the heating effect, has not this defect; but regarded in the direction of the line's length gives perspective effects and sharp images as from a point source of radiation.*

* It should, however, be recognised that a point focus is only obtained in one particular direction, and with a large object (as a thorax) considerable variation of focus, from a point to a line, can occur and cause relative distortion. This equally applies to the focus of the

In a more recent patent (Brit. Patent 244,105/1924) Müller has varied the form of the cathode shield to that shown in Fig. 114A. Whereas the previous arrangement (Fig. 112A) gave an asymetrical obliquely disposed focus upon the anode as shown by Fig. 112B, the focus of Fig 114A is two parallel line foci *a* and *c*, as shown in Fig. 114B. These are both symmetrical and, as well as preserving a point focus in perspective, also further distributes the heating effect on the target.

Philips (Brit. Patent 225,540/1923) claim that the heating of the anode owing to extremely sharp focus is chiefly due to the inner turns of the filamentary spiral and not the more external turns. They therefore make current connections *a* and *d* (Fig. 115) so that the inner turns *d* to *c*, within a circle of 1·5 mm. from the spiral centre, are a " dead-end," such a dead-end conveying no current and so giving no sharply focussed electrons, but serving the useful purpose of mechanically steadying the fragile filament.

Siemens and Halske (Brit. Patent 230,066/7/1924) produce a similar

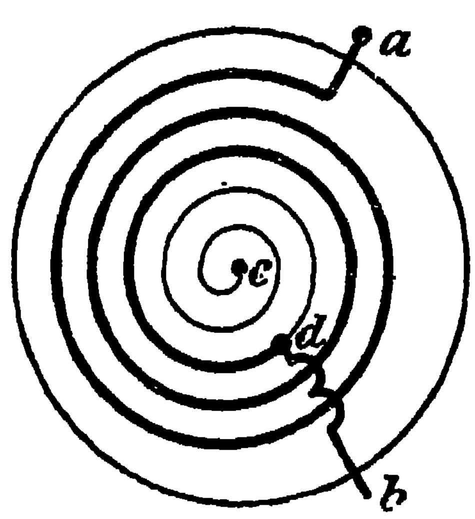



FIG. 115.—Philips Filament.

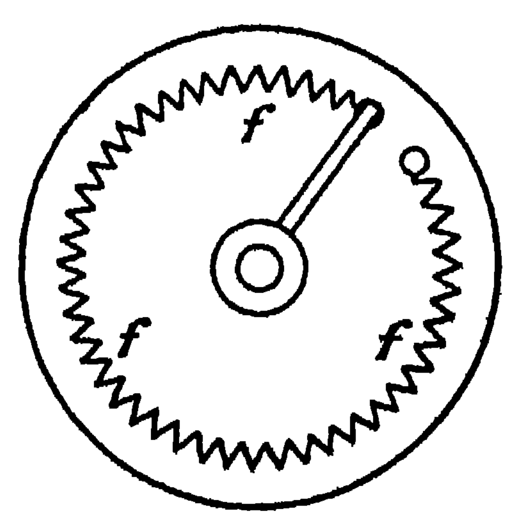



FIG. 116.—Siemens and Halske Filament.

electronic distribution upon the anode by use of a circle filament *fff* within a hood as shown in Fig. 116.

Other refractory metals than tungsten have been utilised for the filament, and the relative thermionic emissions at 2,000° K. are as follows; molybdenum 13, tantalium 7, platinum 6, tungsten 3, carbon 1.

The general choice of tungsten of relatively low thermionic emission is due to its high refractibility, combined with low vapour pressure and cheapness, as compared to other metals.

Recently Langmuir* has used tungsten coated with thorium as a filament. The great thermionic emission of thorium is now much used in the " dull-emitter " type of wireless thermionic valve. Whilst the temperature of operation (1,800° C.) is much lower than that of tungsten, the electronic current is 130,000 times greater than that of pure tungsten. Such coated filaments are however very liable to " poisoning " by the slightest trace of oxygen and the resulting thorium oxide is then much

normal tube. In practice the author has found it advantageous to centre the line focus tube with respect to the patient more than usually towards the tube anode in order to overcome this defect.

* *Phys. Rev.*, 22, p. 359, 1923.

inferior to pure tungsten as regards electronic emission, even though tungsten is itself subject to oxygen poisoning. Thorium-coated filaments can therefore only be operated in the presence of magnesium to act as a " getter " to remove any oxygen which may be disengaged from the electrodes. Such magnesium, deposited upon the glass bulb, is a characteristic feature of triode dull-emitter valves.

Langmuir and Kingdom* have also used a cæsium coating, and for equal electronic emission only 1·34 volts are required across the filament as compared to 4·5 volts for tungsten. The cæsium layer is however rapidly destroyed at the high temperatures used.

Philips (Brit. Patent 211,825/1923) have protected the use of hafnium for filaments to increase the electronic emission, and also the use of zirconium, and titanium (Brit. Patents 216,160/1923 and 223,244/1923). The B.T.H. Company (Brit. Patent 240,166/1924) also protect uranium, used by Coolidge.

It is of interest that, in the analogous region of thermionic rectifiers for high powers, the Western Electrical Company have recently utilised platinum filaments coated with alkaline oxides (Wehnelt cathode) a type of filament used in the original Lilienfeld X-ray tubes.

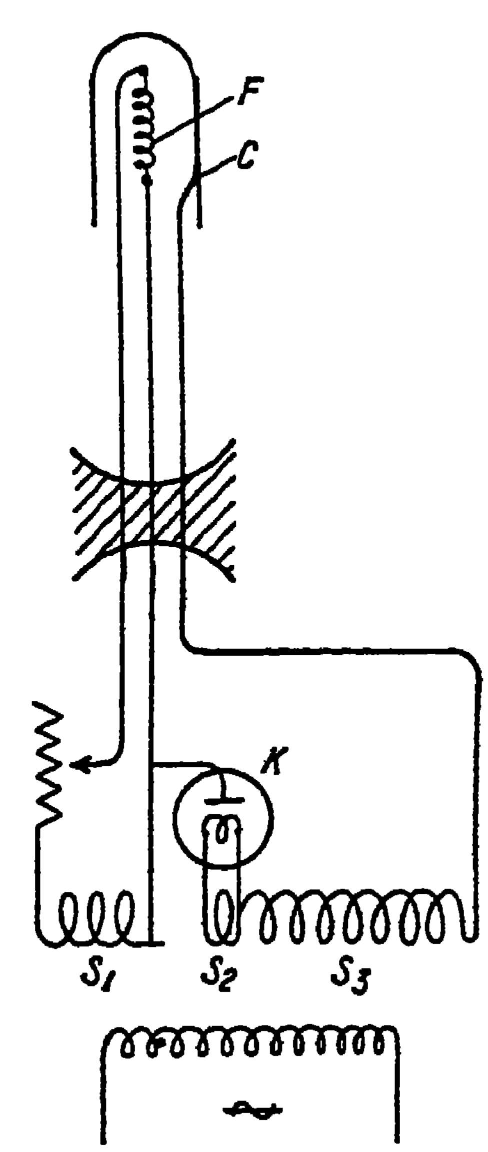


FIG. 117.—Dauvillier Protected Filament.

We have already mentioned that the weak point of the electron X-ray tube is due to the very intense attraction of the mechanically weak filament towards the anode, owing to the powerful electrostatic field. In the Lilienfeld tube (*q.v.*) this attraction is avoided by the interposition of a third electrode, which serves to protect the filament from this electrostatic field, the filament merely serving to provide electrons and taking no part in the main discharge *viâ* the tube.

Similar methods of protection of the delicate filaments of the Coolidge type electron tubes have been proposed.

For example, Dauvillier (French Patent 102,603, July, 1918) has proposed the use of a hood of tungsten C, heated by an internal filament F (Fig. 117). Such a hood is mechanically very much stronger than a filament and its temperature is more easily maintained constant. The use of coatings of emissive metallic films, as of thorium, is also so facilitated.

Alternatively such a hood may be heated by electronic bombardment by application of a potential between an accessory cathode behind the actual operating cathode, which acts as anode to the accessory cathode.

* *Proc. Am. Phys. Soc.*, 1922.

Both methods have been protected in England by Siemens and Halske (Brit. Patent 140,464, June 22, 1918), but this patent has been declared void.

Since the filament acts as one electrode of the high-tension discharge, the heating of this filament cannot be produced by the normal low tension mains, owing to their lack of insulation for very high electrical pressures.

In practice the filament is heated by one of three methods ;—

(1) By a separate, highly insulated, rotary converter motor-generator, or direct-current generator (Fig. 118).

(2) By means of a special transformer the primary of which is suitably insulated against the filament circuit high voltage (Fig. 119).

(3) By a suitably insulated accumulator battery (Fig. 120).

Of these methods the separate excitation of the necessary heating current (about 4·5 amperes at 12 volts), by means of a specially insulated generator is very convenient, but suffers from the disadvantage that if this is excited from the same mains as the large X-ray transformer, when this is thrown upon load, it tends to cause a decrease of current *viâ* the smaller higher resistance filament generator and, as a consequence, the output of this machine, and resulting filament current and electronic emission, falls off at the moment when the emission is most required. This can be compensated for by overheating the filament when not on load, but this is to the detriment of the filament life.

The use of a special filament transformer is the most convenient and most generally adopted method. Such a transformer is a step-down transformer from the electrical main voltage to the filament voltage, and is only specially characterised by the heavy insulation between primary and secondary to prevent access of the high-tension to the low-tension mains.

This method also suffers from the defect that the energy input and filament temperature tends to fall off as the main transformer is thrown upon load, as in the first method.

Similar to the first method, unless the machine is a direct current generator, the filament heating and electron emission is not a steady effect, but varies with the instantaneous value of the current in the filament and therefore, varies with the sine-voltage variation in the low-tension mains. Any difference of phase between the current *viâ* the main and the filament transformer, due to their relative inductances, will result in a difference of phase of the maximum filament heating effect and the applied potential to the tube. As a result the filament current is not at its maximum (Fig. 121A) when the main transformer voltage is at its maximum and, to ensure a sufficient emission, this must be again overheated, or capacity inserted to bring both currents into phase as in Fig. 121B.

Such a synchronisation of main transformer and filament currents becomes of great importance in rapid cinematographic radiography.

The method of excitation by means of an accumulator battery does

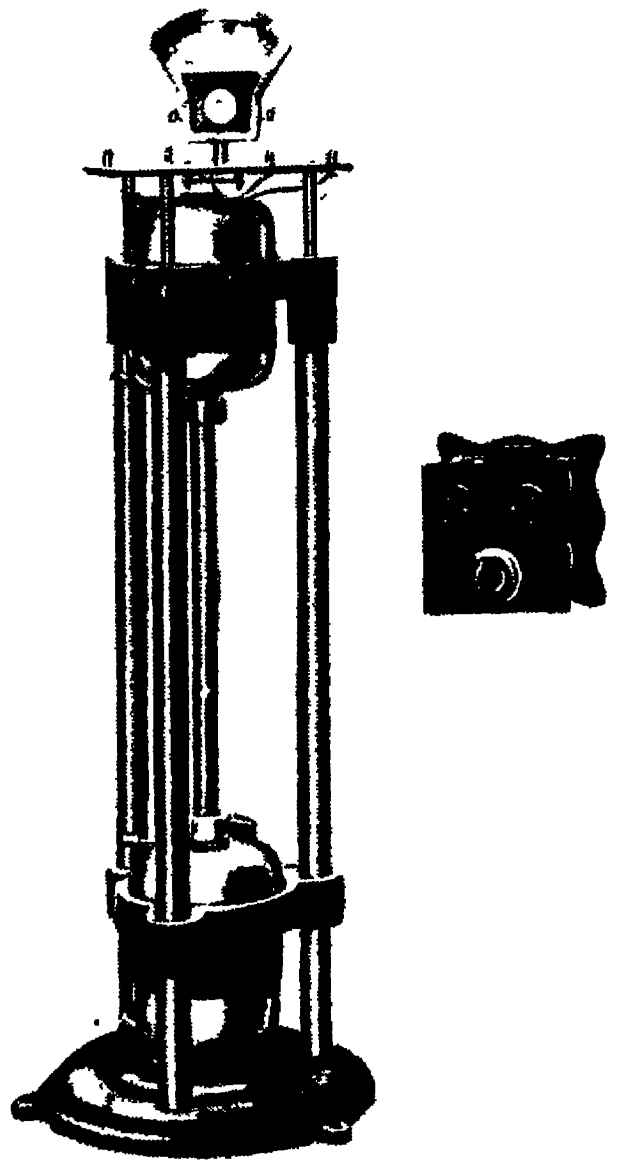


FIG. 118.—Coolidge Filament Motor Generator (A. E. Dean).

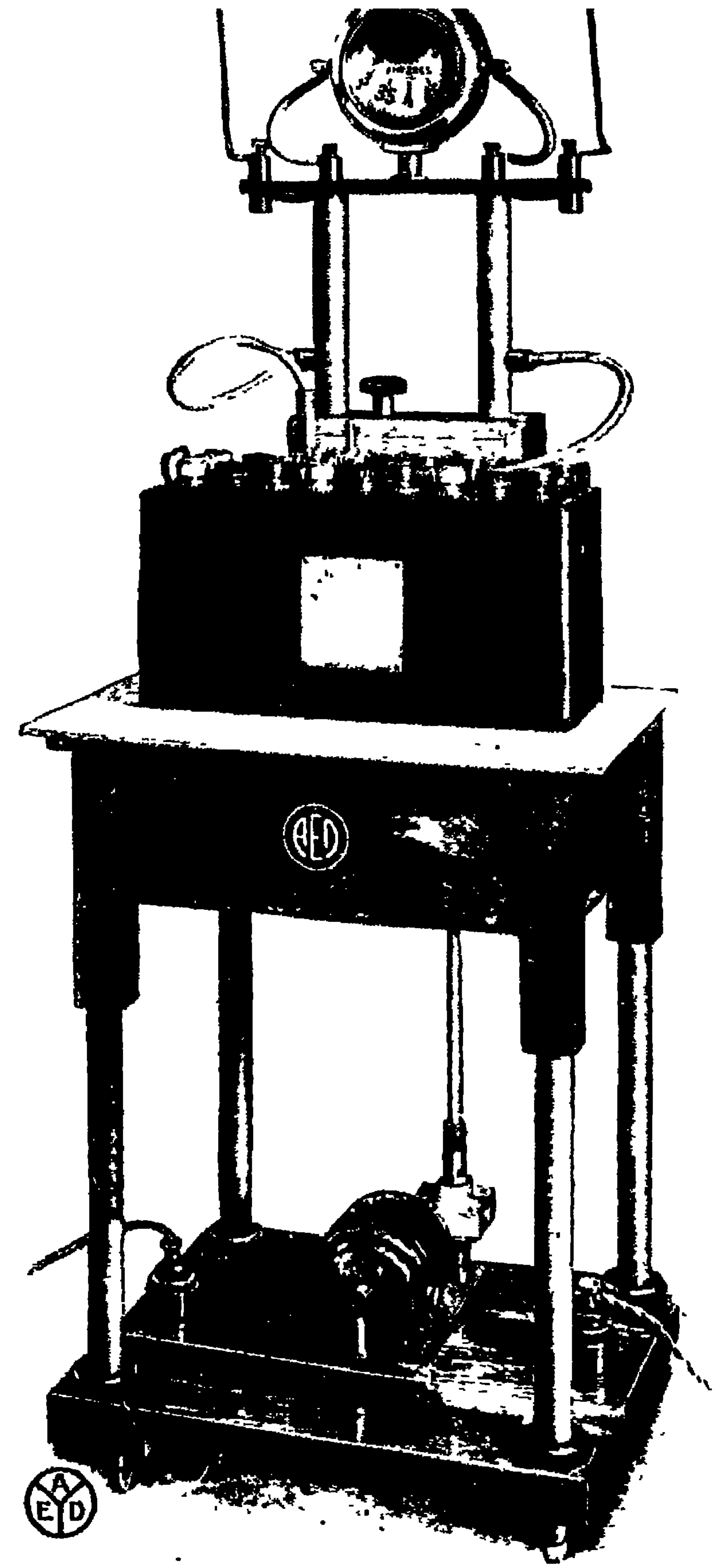


FIG. 120.—Coolidge Filament Accumulators (A. E. Dean).

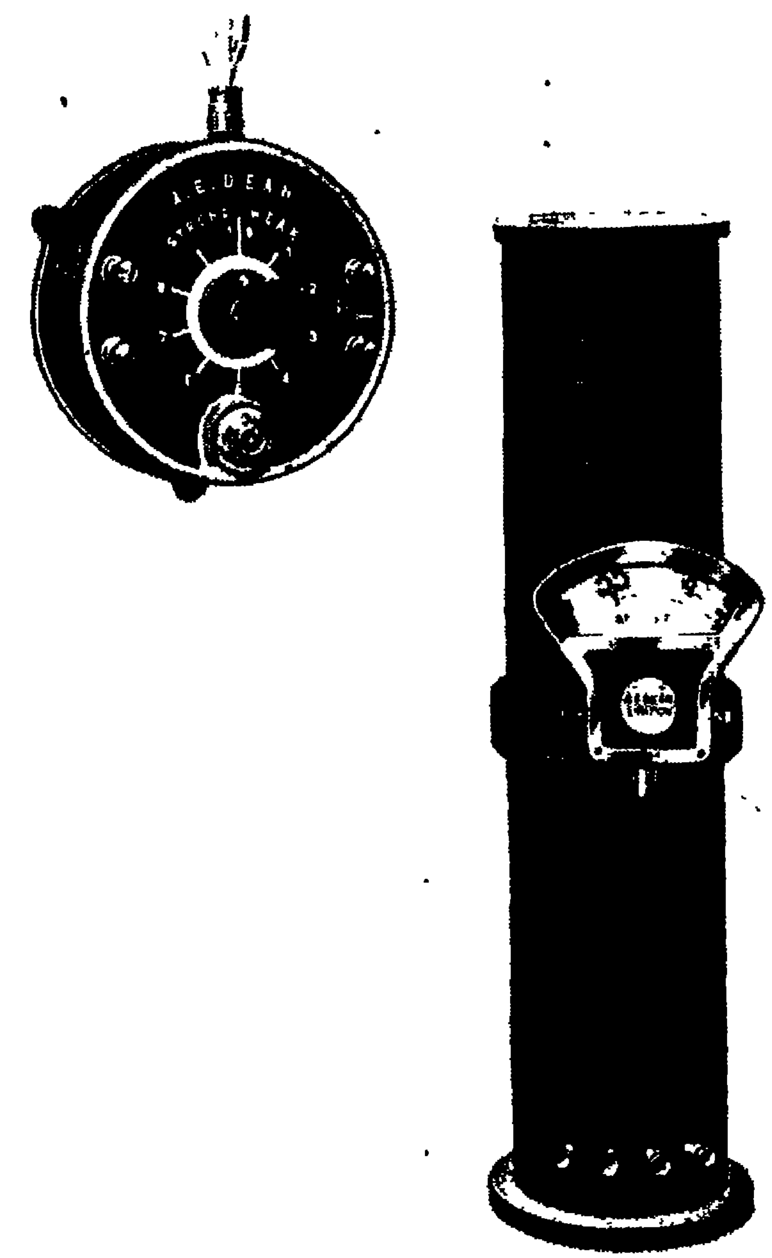



FIG. 119.—Coolidge Filament Transformer (A. E. Dean).

[To face p. 140.

not suffer from this defect, since an entirely separate non-varying filament current is applied. This method suffers however from all the disadvantages of care of maintenance of accumulators, and tends in practice to be displaced by the other more convenient methods of filament heating.

To control the current *viâ* the filament which, in turn, controls the current *viâ* the X-ray tube, it is usual to insert a suitable low-tension variable (sliding) resistance in the low-tension circuit of the exciting alternating generator or transformer, with an ammeter and, more rarely, a voltmeter to give visual control. As these instruments are in the low-

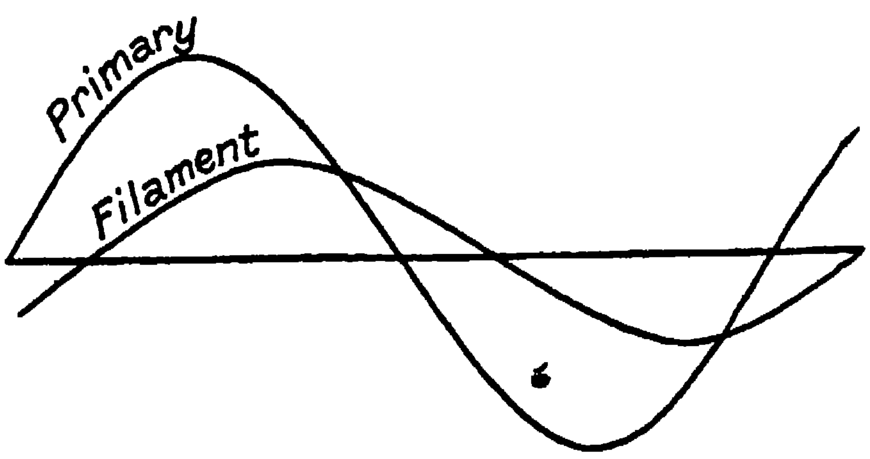



FIG. 121A.

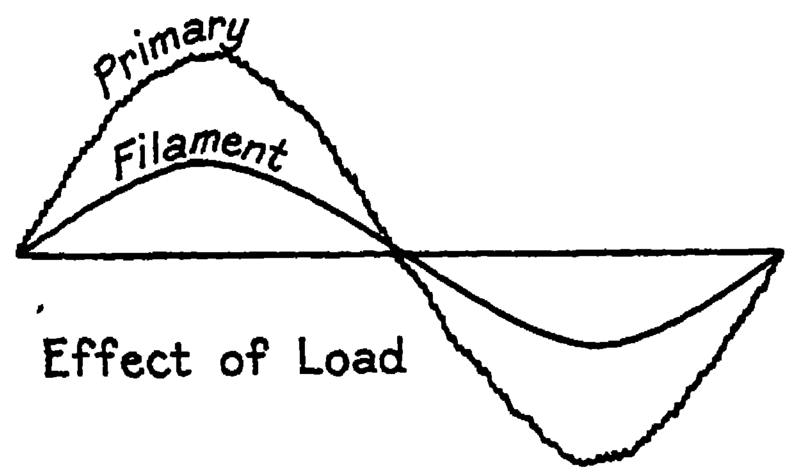



FIG. 121B.

tension circuit they can be mounted directly upon the installation switchboard. In the case of accumulator heating such a control is in a circuit to which the high tension is applied and the controls must be accordingly suitably insulated, and cannot be mounted upon the installation switchboard, an objection to this method of filament excitation.

Kunberger and Lanyon * have advocated the use of a choke-coil control instead of a resistance control on the grounds that the wire of the resistance control oxidises and causes bad contact, and fluctuations of the tube current may so result as high as 7 milliamperes. They describe a

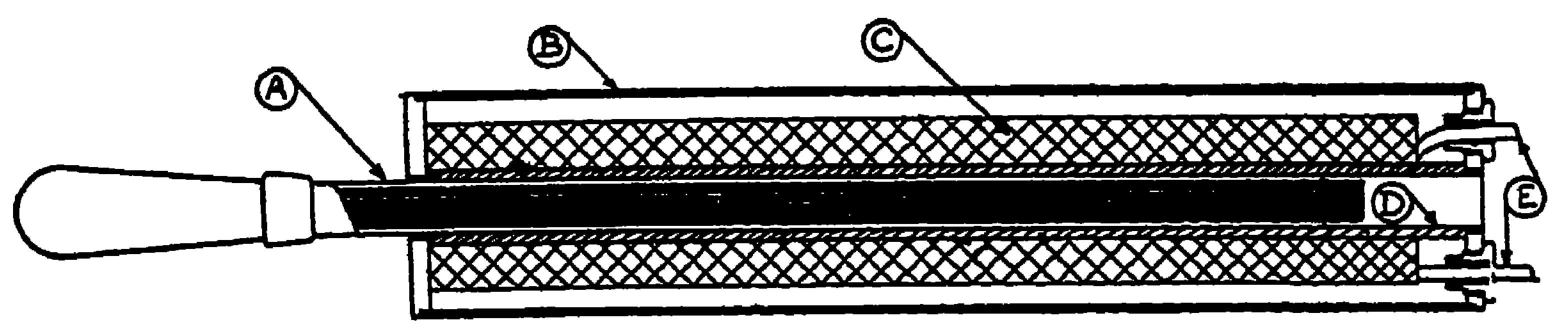



FIG. 122.—Choke Coil Filament Control.

choke coil control shown in Fig. 122, consisting of about 1½ lb. of No. 15 double-covered wire C on a fibre tube D ⅝ in. in diameter and 7 in. long. It is enclosed in a brass case B but this case is split to avoid transformer action. The iron core is a bundle of soft iron wire packed into a split brass tube A which slides into the fibre tube. Adjustment of filament current is made by sliding the iron core in or out of the tube and a filament current variation from 0·5 to 8 amperes is obtained at 12 volts. The regulation is continuous and there are no contacts to cause irregularities.

* *Jour. Opt. Soc. Amer.*, 13, p. 243, 1926.

The greatest advantage of the electronic X-ray tube, over the ionic tube, is that in the electron tube both intensity and quality of radiation are capable of separate variation. The intensity of the X-radiation is only dependent upon the electron emission of the filament and therefore upon the filament current and temperature.

The quality of the radiation is only dependent upon the speed at which the electrons strike the anode as expressed by the fundamental relation $Ve = \frac{1}{2}mv^2 = h\nu = \frac{h}{\lambda}$ and is entirely dependent upon the applied potential.

Unlike the ionic tube, where a definite potential must be applied before shock ionisation, conduction and X-ray excitation can occur, the electron tube will conduct at all voltages, even of only a few volts.

The electronic velocities at such small voltages are very small and such electrons have insufficient energies to give useful X-radiation and are chiefly expended in the production of heat. At somewhat higher voltages and velocities very long wavelength, or soft, X-radiation is produced which, falling upon a patient, have little penetrative power and, being entirely absorbed by the skin, are particularly effective in causing undesired X-ray burns, or, if they penetrate the patient, are scattered in all directions and produce bad photographic definition.

To remove such undesired low quality radiation three methods are available :—

(1) The interposition of a screen of aluminium between the X-ray tube and the patient, to absorb and so to filter out, such soft radiation.

(2) In the usual transformer and rectifying disc method of excitation, to so proportion the rectifier contacts that only those portions of the higher and useful alternating cycle voltage is applied to the tube (see p. 188).

(3) The interposition of a third electrode between cathode and anode, which, given a negative potential in respect to the filament, can repulse the electrons of low velocity and energy.

Occasionally it is arranged for such a "grid" electrode to receive alternate timed positive or negative charge to assist or to repulse the higher or lower speed electrons respectively (see p. 188).

It is to the absence of such low-speed electrons in the ionic tube, that the ionic tube owes one of its greatest advantages over the electron tube.

The speed at which the electrons travel from cathode to anode in the electron tube is not constant. Some distance has to be traversed in order to allow the electrons to accelerate to the average maximum velocity, under the action of the electrostatic field, and this distance serves to move the region of maximum electron velocity towards the anode and from the cathode.

As the electrons approach the anode their mutual repulsions, or

space-charge effect, operates to reduce their average velocities, resulting in a sudden fall of negative potential in the neighbourhood of the anode, since electronic velocity, electrostatic field and voltage are directly related, *i.e.*, if an electron has a velocity and kinetic energy, $\frac{1}{2}mv^2$, this must be related to a voltage product V$e$ and, since $e$ is constant, to V.

In a correctly constructed electron tube residual gas has no part and when present has only an undesired effect of altering the independent regulation of current, or intensity and voltage, or quality.

The gas pressure permissible by the Coolidge patent is ·00005 mm. of mercury or lower, as compared to ·001 to ·01 mm. of the ordinary gas tube. As the result of fundamental researches of O. W. Richardson and others* upon gas ionisation, it has been shown that with a helium or hydrogen tube atmosphere and other requirements as to electrode form and distance to prevent gas ionisation, an electronic conduction can be obtained within the region of pressures between that of the Coolidge tube and ionic tubes, even, under experimental conditions, to pressures as high as ·1 mm. of mercury, *i.e.*, very many times greater than the pressures of ionic tubes.

Philips have utilised this fact in their metal X-ray tube, in which they employ a gas pressure higher than the Coolidge limit of ·00005 mm., but usually below the gas tube limit of ·001 mm. of mercury.

They claim that in such conduction not only has the gas no effect as regards discharge but, by heat conduction, greatly facilitates the removal of heat from the anode.

The production of a negative charge and its distribution upon the glass envelope of the electron tube have already been discussed, as well as the methods of protecting the envelope by means of hoods (p. 110).

The general statement that the electron tube does not undergo colour change of the glass is incorrect, as the glass partakes of a brown or violet coloration, according to whether the glass contains lead or manganese salts.

Whilst the glass of an electron tube does not generally fluoresce like the ionic tube, this appears to be due to a space-charge effect of electrons in the tube atmosphere preventing the glass from being bombarded by electrons, as it can be shown, under suitable conditions, that glass will fluoresce when submitted to electronic bombardment similarly to when submitted to ionic bombardment, as in the ionic tube.

In most electron tubes a certain degree of ionisation and fluorescence of the small amount of residual gas occurs. This residual gas appears to collect in the neighbourhood of the anode neck, where the potential across the glass abruptly varies, and gives rise to a localised fluorescent effect. Whilst such fluorescence shows that the tube exhaustion is not

* See Holst and Oostehuis, *Phil. Mag.*, 46, p. 1117, 1923. *Comptes Rendus*, 175, p. 577, 1922, and Taylor, *Phil. Mag.*, 3, p. 753, 1927.

extreme, it does not infer that such a tube is unsuitable for actual practical operation.

The anode of the electron tube does not necessitate special description as regards its function, being essentially that of the ionic tube anode. It is usually a disc of tungsten held upon a molybdenum, copper or iron head and stem. The latter metals appear to be preferable, owing to their emission of only soft characteristic X-radiation when subjected to bombardment by secondary electrons arising from the target and caused to return to the anode by the electronic space charge. In the case of copper and iron such radiation is soft and absorbed by the glass tube wall, and does not give rise to distortion of the photographic image by acting as an extended source of radiation. In the case of molybdenum the characteristic radiation is hard and can penetrate the glass. Pin-hole photographs of the target at the region of characteristic molybdenum voltage may show the intensity of radiation from the distant molybdenum stem, is greater than from the tube target.

The production of secondary radiation from the stem giving rise to non-focal radiation can be largely prevented by use of an anode hood (*q.v.*), which also, at the same time, prevents electronic bombardment and heating of the glass envelope, deposition of sputtered tungsten upon the glass and resulting liability to glass fracture, by local variation of electrostatic stress due to the presence of such sputtered metal.

Another method of preventing this secondary bombardment is to place the filament very close to the target. This however, owing to the resulting intense electrostatic attraction, tends to cause the filament to unroll and undergo other variations of its shape. It also causes the filament to be heated by the direct radiation of heat from the incandescent target, with resulting variation of temperature, electronic emission and current *viâ* the tube. When a filament is so closely approximated to the target an image of the filament may be actually produced upon the target, due to the direct localised emission of electrons from the coils of the filament to the target which, after long use, shows a sputtered impress of the spiral filament.

Ordinary water cooling of the electron tube target appears to have first originated in Germany (Siemens and Halske, Müller). To Coolidge is due the first attempt to render the cooling more efficient by actually circulating the water *viâ* ducts in the anode itself. Such water-cooling allows the envelope to take an ovoid more convenient and robust form. The original Müller electron tube had a platinum target fused to a copper stem and a filament surrounded by an aluminium shield. It is said that with this tube the use of these metals permit any gas, disengaged by passing very heavy currents, to be very rapidly absorbed.

The chief characteristic of the electron tube is the care taken to render all its component parts free of gas. These methods have been

described by R. C. Robinson and C. N. Moore of the American G.E.C.* in respect to the Coolidge tube and merit further description. The production of Coolidge tubes consists of four distinct operations, namely ;

(1) Preparation of the metallic parts
(2) Assembly.
(3) Exhaustion.
(4) Testing.

In the preparation of the parts commercial tungstic oxide is purified by dissolving it in ammonia and then by precipitation by hydrochloric acid. This precipitate is filtered, dried and the oxide reduced to metal by passing hydrogen over it in a porcelain tube in a furnace.

The spongy reduced metal so produced is allowed to cool in the hydrogen atmosphere, in order to avoid re-oxidation. The powdered metal then obtained is pressed by hydraulic means into rods, which are so fragile that they will not unaided support their own weight. These are heated in an electric furnace in a hydrogen atmosphere at 1,600° C., so undergoing a very considerable loss of porosity and volume, after which they are heated by the passage of a heavy electrical current to just below the melting point of tungsten. The resulting product is a rod resembling steel, but so hard that it cannot be machined in a lathe, but must be fashioned by hammering and grinding at a high temperature.

A finished button of this rod is then cleaned to serve as a tube target and the copper anode is cast around it. This copper is prepared by a process due to Wientraub.† Boric sub-oxide, a by-product of pure borium preparation, is one of the few reducing agents having no affinity for copper. Copper is fused with this oxide and carbon, with the production of nearly gas-free copper, from which any remaining gas may be driven off by heating it in hydrogen, during the tube construction.

The preparation of tungsten for the filament is similar to the preparation of the target tungsten but is a much more delicate operation. This filament is welded by a hydrogen arc to its molybdenum supports.

To remove occluded gas all parts are fired at 900° C. for one hour and then assembled in the glass bulb. This bulb is blown automatically by special machinery operated by girls, who seal in first the exhaust tube and then the cathode and anode sleeves, in which the respective electrodes are inserted.

The methods of high-vacua exhaustion have been already described, and, in the process of Coolidge tube evacuation, the process consists of final evacuation by means of the Langmuir condensation pump, backed by a rotary pump. Ingress of mercury to the X-ray tube is prevented by means of a liquid air trap. The tube is then heated in a large oven, after which it is heated in a vacuum oven to allow the application of

* *Amer. Jour. Rönt.*, 7, p. 254, 1920.
† *Jour. of Indust. and Eng. Chem.*, 5, p. 106, 1913.

greater heat without danger of collapse of the softened walls due to external pressure. This oven is arranged as an X-ray tube oven, *i.e.*, with means to apply the necessary operating electrical potential and with protection against exit of X-radiation from the oven, dangerous to the operator. Contacts are present in the low-tension circuit of the operating transformer not to permit the opening of the oven whilst the high tension is existent.

Before this method of operation, the tube is merely heated for three-quarters of an hour to remove water vapour, carbon dioxide, etc., from the glass walls and metal parts. After this it is operated as an X-ray tube, *i.e.*, potential is applied and gradually raised until all signs of glass fluorescence, signifying ionic bombardment and presence of gas, are absent, and the tube is therefore operating with a purely electronic discharge.

At this stage, which is much above the designed practical limits of operation, the seal is heated. This results in the evolution of further gas from glass decomposition at the region of sealing and the tube is allowed to remain upon the pump for some time and the fused glass finally pressed together and sealed by pressure together of the walls.

The perfection of vacuum in the Coolidge tube is extreme. Holbeach * has described and exhibited to the writer Coolidge tubes which were deliberately overloaded by a fourfold load, in which the copper anode has entirely fused around the target and allowed this to slip, yet in spite of this, owing to the care taken in preparation, no gas has been evolved sufficient to prevent a purely electronic discharge. The vacuum of the Coolidge tube is stated to be in the neighbourhood of $\frac{1}{10000000}$ atmosphere.

To test the tube it is operated at a 10-in. gap for one or two hours, then allowed to rest for a day and again operated at a 6-in. gap with a white-hot target. Those tubes showing the presence of occluded gas by fluorescence are rejected for re-exhaustion. After varying intervals of rest a second and a third similar test are given. As a result of these tests the tube when supplied will often show purple coloration due to manganese salt formation in the glass and a frosted area upon the target face. Within reason such a frosted area is not objectionable but, if the target is very greatly pitted, or is cracked, it is obvious that all the care taken to produce a sharp focus in a fine focus tube must be wasted, and such a tube is rejected.

## COMPARISON OF IONIC AND ELECTRONIC TUBES

The theoretical advantages of the electron tube are independent control of tube intensity (current) and quality (voltage), great constancy with absence of the disagreeably inconvenient softening devices, the

* *Brit. Jour. Rad.*, 22, p. 20, 1926.

possibility of high loads, space economy, non-intermittent operation, and self-rectification.

Upon theoretical grounds there is little to be said in favour of the gas tube, still generally used in England. The main advantage is the somewhat artificial one of much lower cost, and more importantly that, in the gas tube, due to breakdown not occurring until a definite ionising potential is reached, the tube does not emit so much unuseful soft radiation, likely to produce burning of the patient. Means of overcoming this disadvantage in the electron tube have already been described. Certainly there is no means whereby the ionic tube can be made self-regulating for fine and medium foci, as in the Müller self-focussing electron tube later described.

The ionic tube is stated particularly to favour the particular intermittent discharge of the induction coil, the use of which is greatly decreasing, and which is characterised by a sudden potential rise and tube breakdown. There does not however appear to be any positive theoretical grounds for such an advantage. Certainly any such advantage is more than overbalanced by the self-rectifying properties of the electron tube, dispensing with rotary apparatus and rectifiers, for portable apparatus, where the tube is not allowed to operate with a heated target. Portable apparatus is becoming constantly less and rarely fitted with gas tubes.

The discussion of the relative merits of ionic and electronic tubes is equally as vexed as the analogous induction coil and transformer discussion and indeed, the two discussions are intimately related.

Much that has been claimed as regards gas-tube superiority over the electron tube is, as in the analogous coil and transformer controversy, obviously a matter of opinion and conservatism rather than of fact. Equally as the transformer is in practice replacing the induction coil, so the electron tube is replacing the ionic tube, and there is little doubt that if there was an equality of price, the electron tube would be still more widely used, and the transition be more rapid.

All comparisons of apparatus must be considered with reserve, since besides theoretical advantages in practical tests the results equally depend upon design and quality of the particular apparatus. In comparison of a coil with a transformer, the transformer may be of good design and the coil of poor design, or conversely, and the results for two particular instruments are not necessarily valid for the more general comparison. Similarly in comparing ionic and electronic tubes the ionic tube may be of good design and manufacture whereas the electron tube is of poor design and manufacture, or conversely. Unfortunately most tests have been made with only a few designs of electron tubes, whereas many excellent ionic tubes are available and, until the manufacture of electron tubes becomes more a matter of competition, a definite opinion cannot be

obtained. Further, allowance must be made for the particular targets used and whether the tubes are or are not being operated in the region of the targets' characteristic radiations. Some German tubes employ a platinum target, whereas the American tubes employ a tungsten target, and, where fluorescent screens come into question, the screen fluorescence will affect the results.

Perhaps the most reliable English data is that of Moore * which however, suffers from the above limitation that only particular tubes were used. As the result of very careful experiments with an induction coil, rectified transformer current and constant potentials supplied by both a three-phase rectified current and a "transverter" current, Moore arranged the relative values of the tubes, as based upon minimum heterogeneity of the spectra and the minimum range of wavelengths excited in appreciable quantity as follows ;—

(1) Coolidge, or gas tube, excited at a constant potential.

(2) Gas tube at a large alternative spark gap, either on a transformer apparatus or an induction coil.

(3) Gas tube working at a medium alternative spark gap on an induction coil.

(4) Coolidge tube on a transformer apparatus.

(5) Coolidge tube on an induction coil, particularly with large currents *viâ* the tube.

The results therefore show that whereas on a constant potential source the selection of a gas or Coolidge tube is of relatively little importance, with the other, more usual, methods of excitation the gas tube is superior to the Coolidge tube.

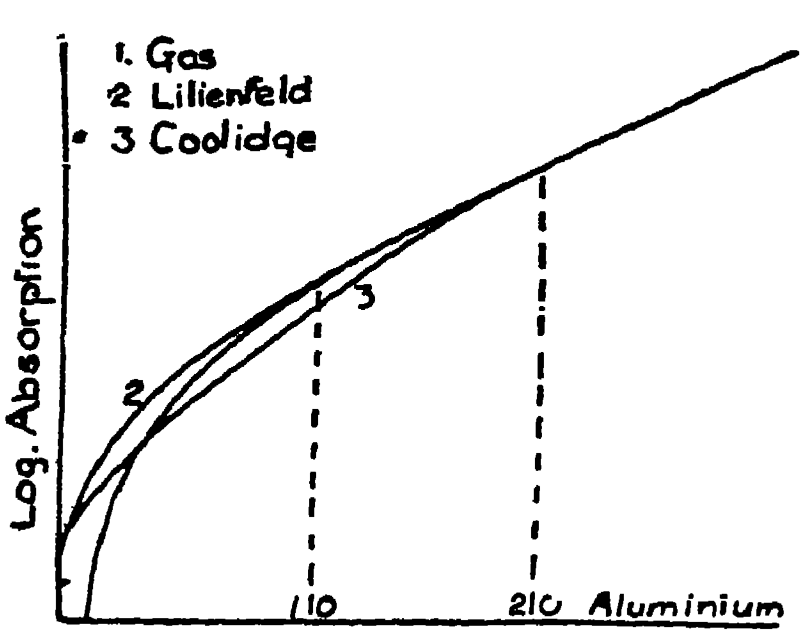



FIG. 123.—Homogeneity Curves of Müller Gas Tube, Coolidge Tube and Lilienfeld Tube.

A more comprehensive series of tests as regards particular tubes are those of Wintz,† who gives data for German Coolidge type, Lilienfeld and Müller "boiling-water" tubes. In this connection it may be remarked that the particular gas tube used is undoubtedly the best gas tube for the purposes of deep therapy and for this reason is very extensively used in England.

The data of Wintz are based upon the thickness of filter (aluminium) necessary to give homogeneity of radiation at equal intensity for therapeutical purposes. The results are combined in a single figure in Fig. 123, and would show the relative value of the tubes as Lilienfeld tube, Müller gas tube and Coolidge type tube, *i.e.*, with the Lilienfeld tube homo-

* *Brit. Jour. of Rad.*, 20, p. 73, 1924.
† "Unsere Methoden der Tiepen-therapie," p. 67, 1920.

geneity is more quickly reached and a thinner filter is so necessary which, in practice, results in less loss of X-radiation energy by filtration and gives for equal depths a greater depth dose. Ledoux-Lebard and Dauvillier * in France, have also described tests upon Lilienfeld, Coolidge and Müller gas tubes. These were tested as regards time of exposure for equal photographic intensity, with constant potential, sine potential and rectified sine potential. The method was in all cases to use the same potential (45 kv.), the same current (5 milliamperes) and same distance of the focus to plate (65 cm.), and to vary the time of exposure to give equality of photographic results. These results were: Lilienfeld tube 3 seconds, Müller gas tube 4 seconds, Coolidge tube 5 seconds, which represent the order of relative value agreeing with the results of Wintz.

The results of these two comparisons would appear to show that the Coolidge type tube is not necessarily the most efficient electron tube and that the radiation of the Lilienfeld tube is superior. Against the Lilienfeld tube is the somewhat greater complexity of circuits, but the present author, from extensive use of this tube in Germany, can state this is a theoretical rather than a practical objection. A further advantage of this tube is its massive and particular construction, which allows the use of alternating current to give 500 impulses per second as against 100 per second with the Coolidge type tube, the construction of which does not so readily allow the use of such a high frequency of excitation.

The author's own practical experience embraces the Lilienfeld tube, various gas tubes, and Coolidge tubes. He has practical experience of the German Coolidge type tubes, very extensively used in Germany, with very satisfactory results.

Of the electron tubes we have to distinguish and discuss in the following pages various types, namely ;—

(1) The two-electrode filamentary tubes with high vacua, of which the Coolidge tube is the best known type.

(2) The three-electrode filamentary high-vacua tube, of which the Lilienfeld and the Müller self-focussing tubes are the best known types.

(3) The two-electrode filamentary tube with low vacuum, as the Philips "Metallix" tube.

(4) The two-electrode non-filamentary high-vacuum tube. (Lilienfeld *Aonröhre*, or auto-electronic tube.)

## THE COOLIDGE TUBE †

The Coolidge tube, in its adaptation for various specific purposes, has received the most extended development of any electron tube. In consequence, the types range from the "baby" Coolidge tube for dental

* *Comptes Rendus*, 173, p. 382, 1921.

† For further details of Coolidge tubes, see Appendix II., p. 534.

purposes, of length only 4½ in., to deep-therapy tubes of length 40 in. The relative sizes of these tubes are shown in Fig. 124, where the respective tubes are as follows ;—

(1) " Baby " dental tube.
(2) " Radiator " tube with lead-glass bulb and transparent glass window.
(3) " Radiator " dental tube.
(4) " Radiator " tube with removable lead-glass shields.
(5) Universal tube.
(6) Air-cooled deep-therapy tube.

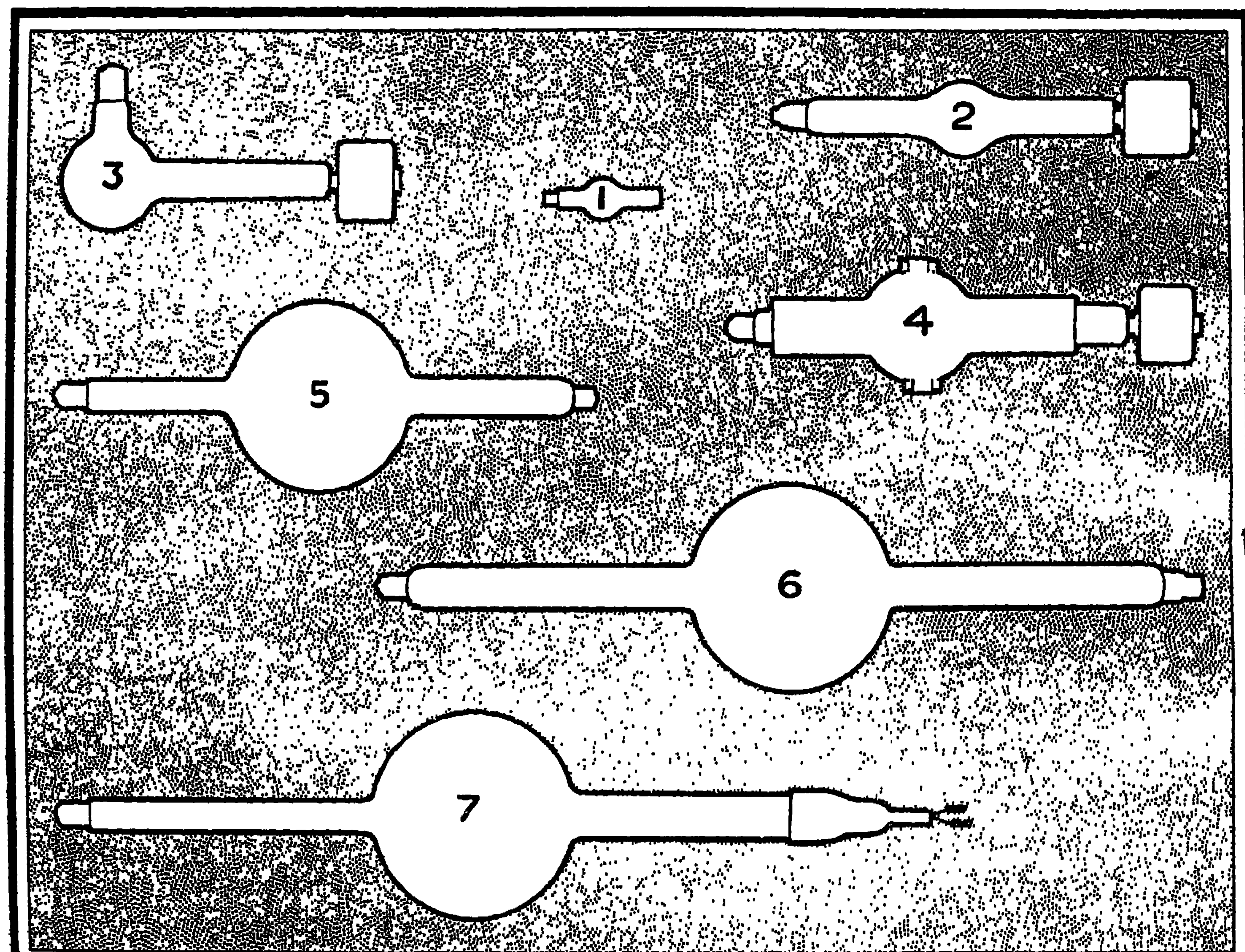



FIG. 124.

(7) Water-cooled deep-therapy tube for 250 kv.

A more striking comparison of the smallest and largest Coolidge tubes is given by Fig. 125.

The " baby " Coolidge tube is shown half its normal size in Fig. 126. With the small size of the filament focussing device, the focal spot would be too small and tend to pit the target were it not for the molybdenum pin which projects through the centre of the filament spiral (Fig. 126) and, by electrostatic repulsion, causes a broadening of the electron beam. This tube operates in oil at 56 kv. (maximum) and 10 milliamperes, and is intended for use with a wall-type dental apparatus

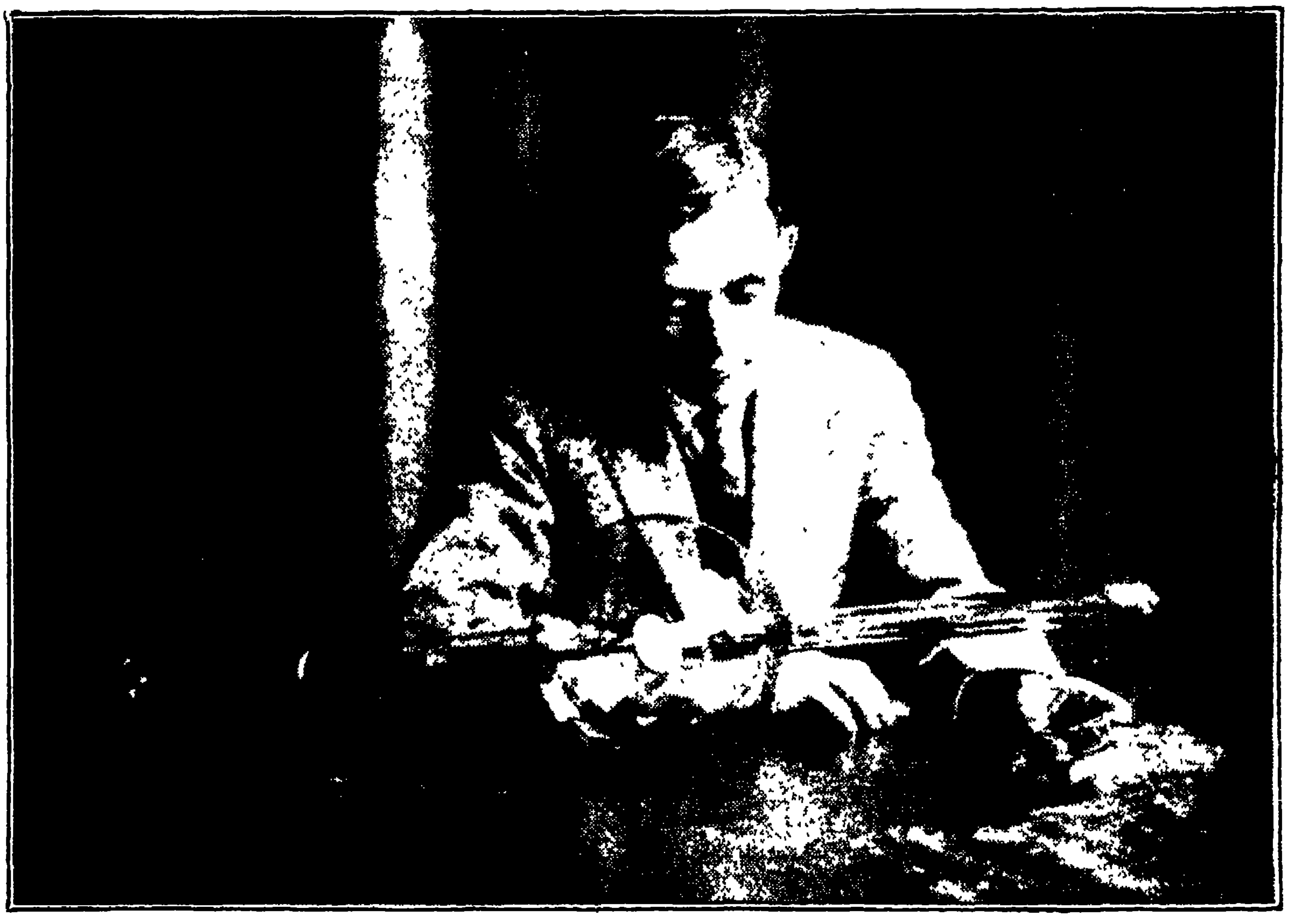


FIG. 125.—Contrasting Sizes of Coolidge Tubes.

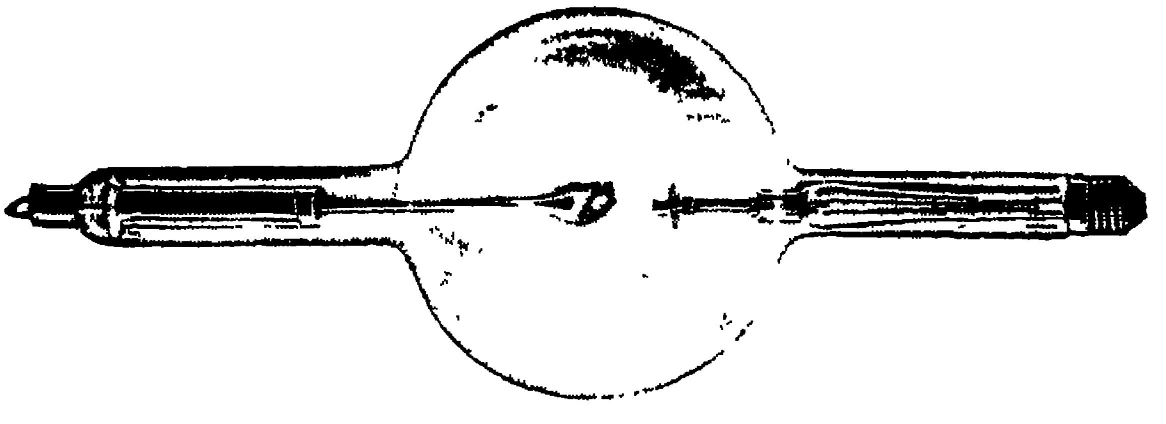
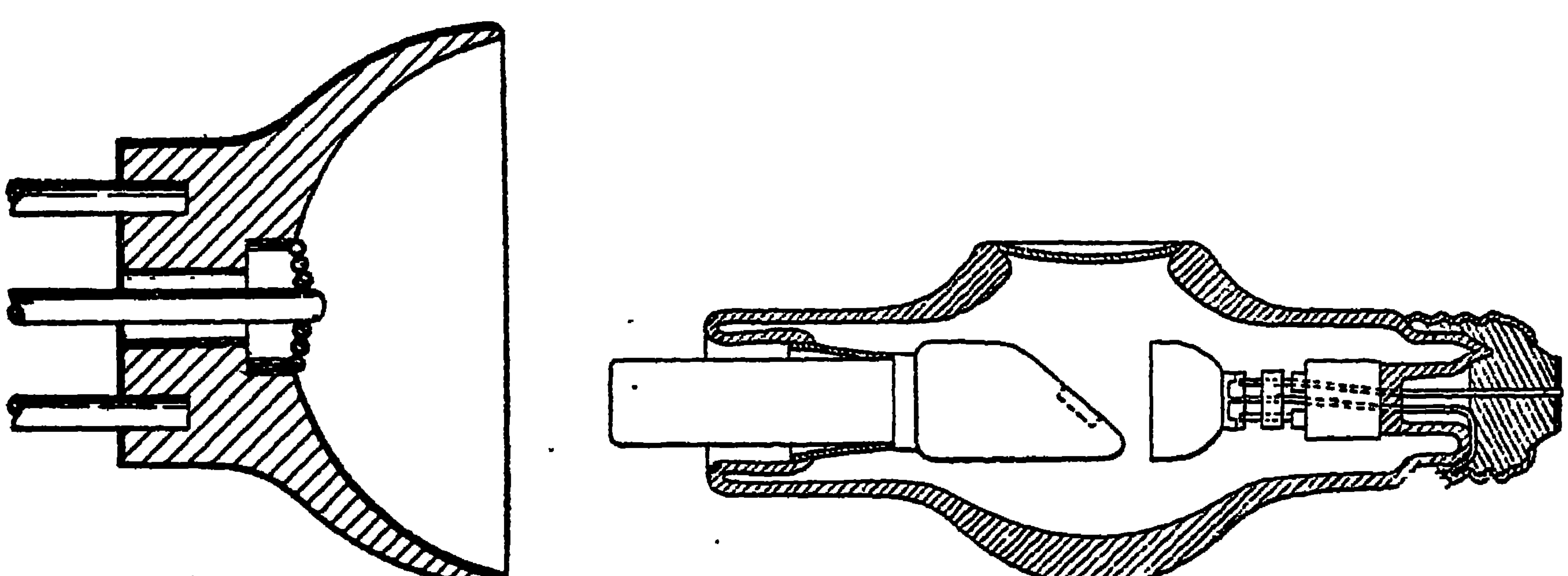


FIG. 128.—Universal Coolidge Tube.

[To face p. 150.

distinguished by both the high-tension transformer and the X-ray tube being in a common oil tank (Fig. 127).

The glass of this tube, in the stippled portion of Fig. 126, is made of 55 per cent. by weight of lead and, being $\frac{1}{8}$ in. thick, offers ample X-ray protection at the voltage intended for operation, the lead equivalent being $\frac{1}{32}$-in. sheet lead. The window through which the useful X-rays pass is made of thin lead-free lime glass. The focal spot is $\frac{1}{8}$ in. diameter. The angle of the target has been made 60 degrees instead of the usual 45 degrees for the reason that if, by overloading, inverse current passes, it is desirable that the inverse current which comes from the focal spot in a direction normal to the working face of the target will be intercepted by the molybdenum focussing device. It would otherwise impinge upon the glass wall of the tube and probably crack this by local heating. The use of the larger target angle brings the normal to the face of the target



Cathode.

FIG. 126.

nearer to the tube axis and hence permits the use of a smaller focussing device than would otherwise be necessary, important in this case where it is so desirable to make the tube small. The cathode filament requires a heating current of only 2·2 amperes at 2·6 volts, and so permits the use of a very small filament transformer.

The distinguishing feature of the second Coolidge tube is the use of a lead-glass envelope and soda-glass window, and has been illustrated in Fig. 41, and the same power tube, but with a soda-glass envelope with external lead-glass shields, has also been illustrated in Fig. 42.

Such tubes have sufficient X-ray protection for the purpose for which they are intended, *i.e.*, use with the smaller portable radiographic installations usually known as "30-milliampere" apparatus, working at a voltage of 50 to 70 kv. with self-rectification.

The form of the cathode has been shown in Fig. 111 (2) and consists of a hemispherical molybdenum bowl. Such tubes have a target sufficiently heavy to ensure that their temperature, during operation, does not rise above the red-heat temperature. In consequence they are self-rectifying

and no rectifying device is necessary, which is of particular value in portable installations, able therefore to work directly from an alternating current supply. Loss of heat by radiation is promoted by the heavy copper anode head with a copper stem in direct connection with the external finned radiator. The bulb diameter is 3½ in.

For more extensive radiography, *i.e.*, extended radioscopic work of the alimentary canal, etc., the tube of election is the Universal tube (Fig. 128).

The filament of this tube is shown in Fig. 111 (1), and is surrounded by

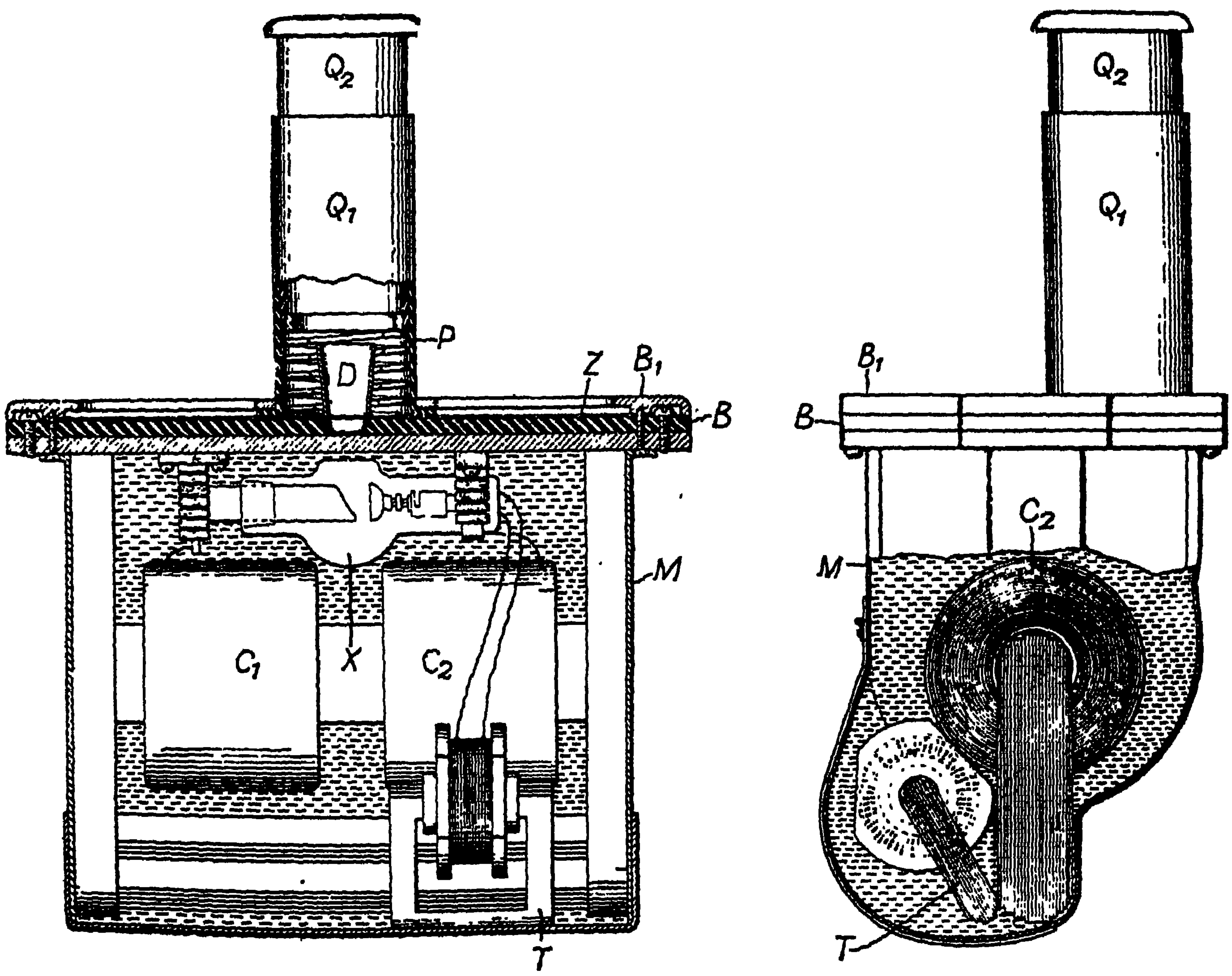



Fig. 127.—Dental Unit, with "Baby" Coolidge in Transformer Tank.

a flanged focussing hood B. This filament requires 4 to 5 amperes at 10 to 12 volts, supplied either by a separate transformer or by an accumulator battery, the former method being practically most convenient, but more liable to cause fluctuations, for reasons already given. Connection of the tube to the heating current leads is made by means of a screw socket. The target of this tube has been already illustrated in Fig. 77 (3) and consists of a tungsten head C, attached to a molybdenum stem D and supported by a split-iron tube E.

The envelope has a diameter of 7 in. and is of soda glass, as it is only intended for use in fully protected apparatus, as a couch or screening stand. The length is 22 in.

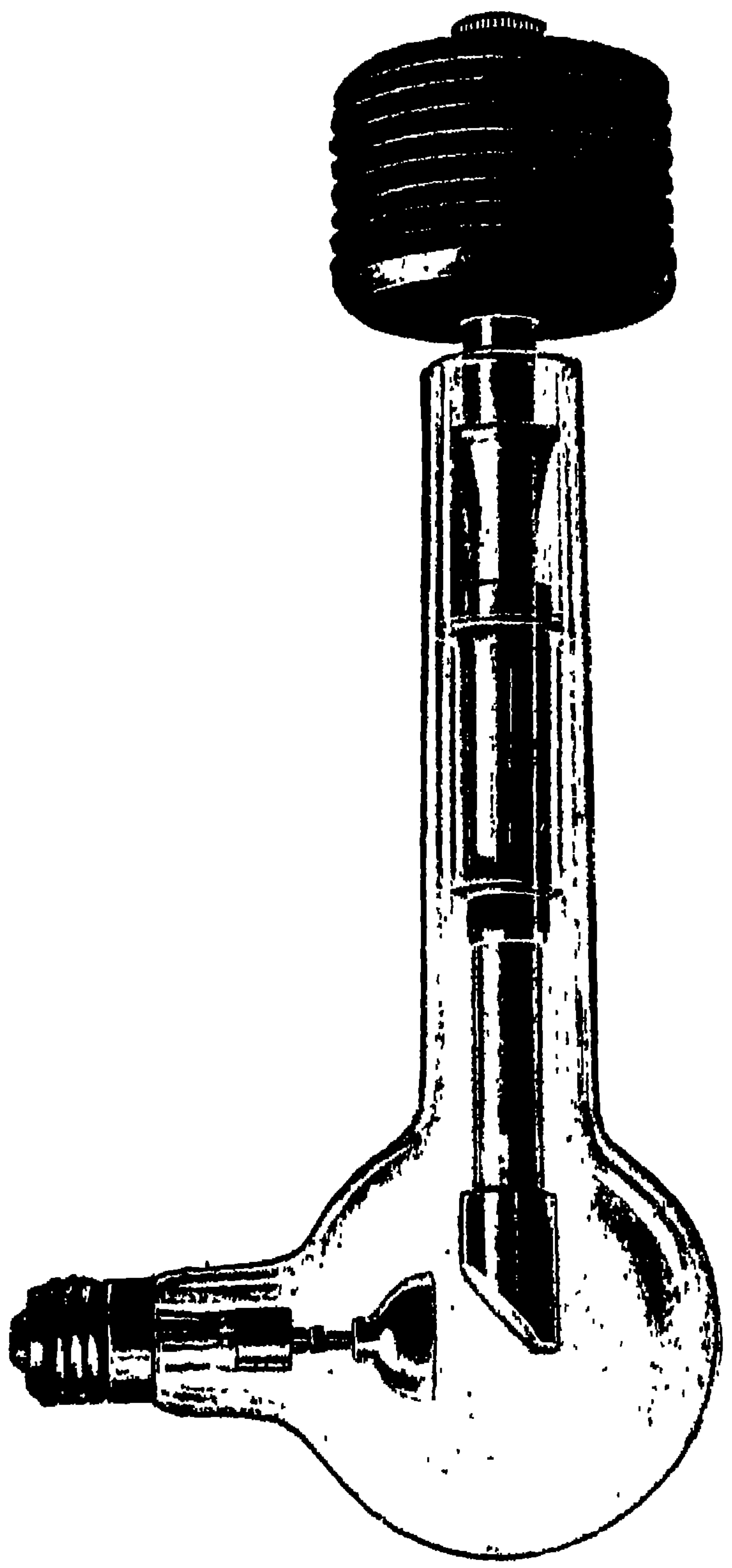


FIG. 129.—Dental Coolidge Tube.

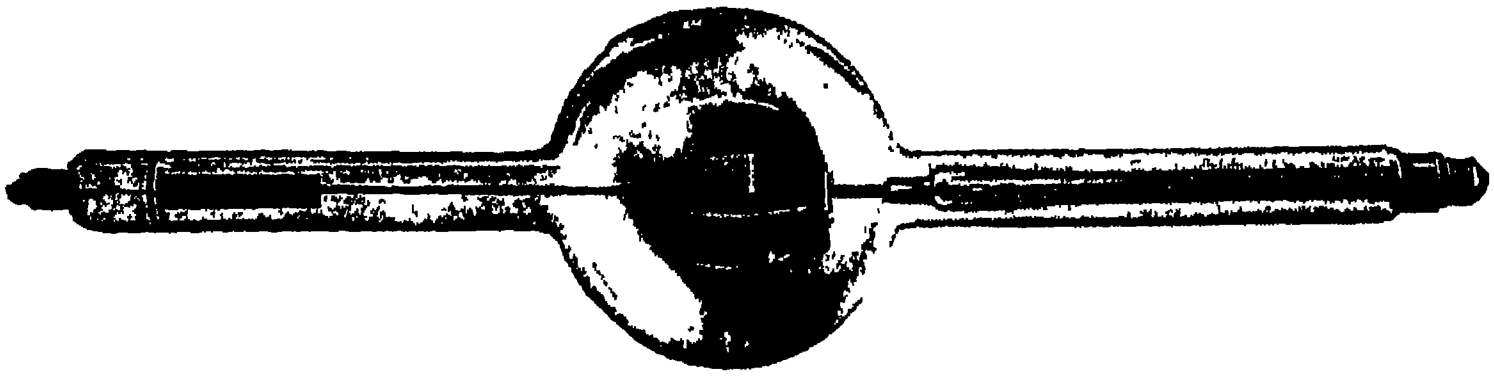


FIG. 130.—Deep-therapy Coolidge Tube (Air-cooled).

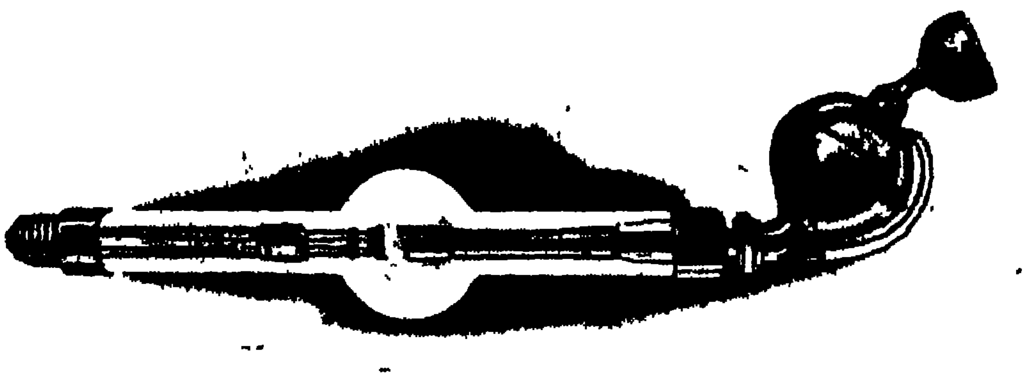


FIG. 131.—Müller Electron Tube (Water-cooled).

[*To face p.* 153.

These tubes are also able to supply radiation for therapeutic purposes and are, by variation of the relative positions of filament and cathode hood, given various foci defined as fine, medium and broad. The fine focus is intended for fine detail radiographic work and low-current fluoroscopic work, whereas the broad focus is intended for therapeutic work and heavy "flash" radiography. Between these limits is the medium-focus tube for radiographic, fluoroscopic and light therapeutic work, *i.e.*, as an all-round tube.

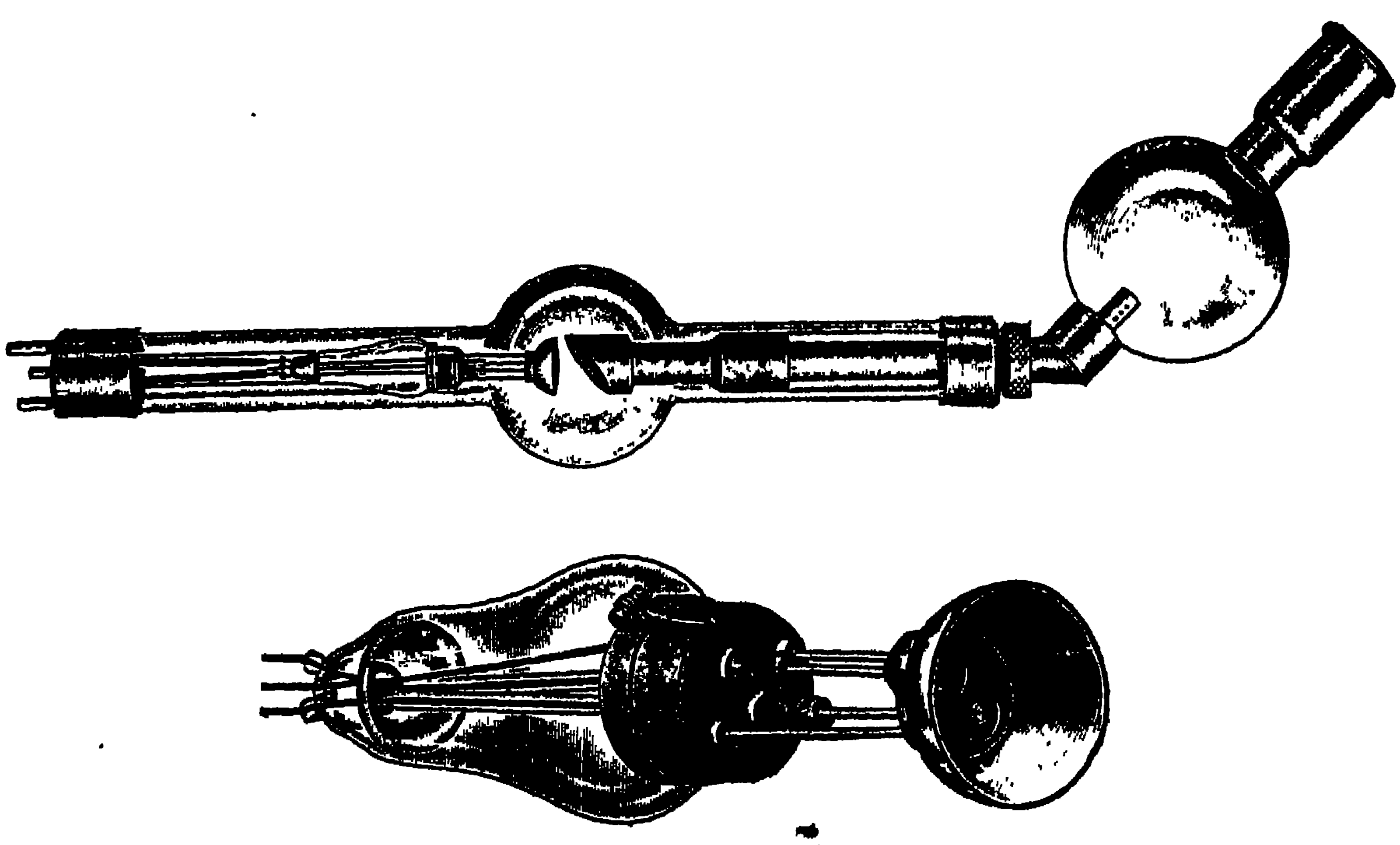
For a 6-in. gap the current limit of the fine-focus tube is 25 milliamperes, for the medium-focus tube 50 milliamperes, and for the broad-focus tube 80 to 90 milliamperes. For other gap distances the currents should be correspondingly modified. These tubes are so designed as to radiate directly all the heat generated at the anode, which becomes white hot. For too heavy therapeutic loads the limit is not the actual radiation of heat, but the effect of the heat upon the glass envelope, which causes gases to be evolved from the glass and loss of vacuum or even actual fusion of the glass envelope. For this reason air cooling of the envelope is recommended, especially when the tube is used in a totally enclosed tube box with bad ventilation.

Unlike the previous "radiator" self-rectifying tubes, as the target at white heat itself emits thermionic electrons, the tube is not self-rectifying and is intended for use upon rectified transformer current.

The dental tube (Fig. 129) is characterised by the particular arrangement of the electrodes, which are otherwise similar to those of the "radiator" tubes. This right-angled arrangement allows the rays to be emitted in the direction of the long axis of the anode and so permits more convenient use for the purposes of dental radiography. Secondly and more importantly the tube is actuated by a transformer which has one secondary terminal earthed and, as this earthed terminal is connected to the cathode, the bulb of the tube, being at roughly earth potential, can be closely approximated to the patient without fear of shock, the only high-tension connection being to the distant anode terminal. This close approximation greatly avoids the distortion commonly present in distant dental radiography. The tube operates with 10 milliamperes at a 3-in. gap between points and is operated for specific periods by means of a time switch, the small distance between plate and target allowing work to be effectively carried out with this comparatively small tube current. By means of the time switch the operation merely depends upon closure of the primary transformer circuit after the time switch has been set, and the operation is therefore extremely simple and intended for unskilled use.

The air-cooled deep therapy tube (Fig. 130) is essentially similar to the Universal tube, but is of larger dimensions, having a bulb 8 in. in diameter and a length of 31 in. (74 cm.). It will pass 8 milliamperes at 200 kv. continuously.

The deep-therapy water-cooled tube (Fig. 531, p. 534) is the most powerful commercial tube and operates with no less than 6 to 7 kw. of energy at voltages from 200 kv. to 250 kv. or even 300 kv., and, if necessary, with currents of 50 milliamperes and even above. The water-cooling apparatus has already been described upon p. 119. The special feature of this tube is that the cooling water is actually circulated *viâ* ducts in the anode itself closely situated behind the flat target. The cathode is similar to that of the Universal tube, except that it has a central pin as in the " baby " Coolidge tube in order to broaden the focus. The anode stem of this tube is a copper tube joined to the re-entrant glass wall by



Cathode.

FIG. 132.—Double Focus Tube (Messrs. Phönix).

means of a platinum seal. Similar tubes to operate at 300 kv. have an overall length of 80 cm.

*Other Coolidge Type Tubes.*—In Germany various tubes similar to that of Coolidge have been independently developed, notably by the A.E.G., Siemens and Halske, Müller and the Phönix Companies. A few of these tubes use a platinum and not a tungsten target.

The A.E.G. tubes are essentially the same as those of the American company, but are generally of longer length up to 80 cm.

The Siemens tube is characterised by the use of iron instead of molybdenum for the anode stem and the use of boiling-water cooling. The use of iron is stated not to permit the tungsten to obtain a temperature above red heat, but those tubes seen by the writer have however been running at white heat.

One of this company's tubes intended for therapy at 200 kv. and 3 milliamperes is distinguished by a right-angled arrangement of electrodes as in the Coolidge dental tube, but the target face, of very large

area, is directly perpendicular to the anode axis instead of oblique as in the above-mentioned Coolidge tube.

Müller has constructed various types of electron tubes, chiefly distinguished by the use of boiling-water cooling, so allowing the reduction of tube diameter to a robust ovoid form, as well as by the use of various ingenious self-focussing or linear-focus cathodes which merit separate description (pp. 137 and 190). The largest tubes are intended to operate at 220 kv. with 4 to 5 milliamperes for therapy and loads of 1,000 milliamperes for one-tenth second at 40 kv. for rapid radiography (see Appendix III.).

A tube requiring notice is the bifocal tube of the Phönix Company (Fig. 132), the cathode of which is shown in detail (Fig. 132). The cathode shield is seen to contain two filaments, one of which gives a broad focus upon the target for long-continued screening operations and the other gives a sharp focus for rapid heavy current radiography. Various arrangements of these double filaments, above each other, as well as shown in Fig. 132, will be found in the patent specification (Brit. Patent 211,450/1923). This bifocal arrangement results in the necessity of three high-tension leads and a high-tension switch, which makes alternative connection to either filament. Müller claims that his " auto-focus " tube overcomes the necessity of such external switching arrangements.

The double cathode tube of the Phönix Company is made either with radiator or water-cooled anodes and the relative advantage of water cooling over radiator cooling may be appreciated from the fact that whereas at 60 kv. only 3·5 milliamperes can be safely passed *viâ* the radiator tube, 6 to 8 milliamperes can be passed *viâ* the similar water-cooled tube at 60 to 40 kv.

## THE LILIENFELD TUBE

Whilst extensively used in Germany, where its merits have been well proved, this tube, with a few exceptions, has not appeared in England for reasons already given. The present writer can speak at first-hand experience of the merits of this tube both for radioscopy and radiotherapy. Reference has already been made on p. 148 to comparative tests upon this tube by Wintz, Ledoux-Lebard and Dauvillier. Wintz states: * " This curve is obtained with a Lilienfeld tube. Here the homogeneity point is about 9·5 mm. of aluminium, therefore roughly the same value as the self-hardening gas (Müller) tube. Curve 4 is the absorption curve of a Coolidge tube. Here we first find the homogeneity point at 20 mm. of aluminium. This result is specially important in the critical consideration of the Coolidge tube. We at once see that the Coolidge tube gives an extraordinarily great proportion of soft radiation.

* Seitz and Wintz, " Unsere Methoden der Tiepen-therapie," p. 67, 1920.

In order to obtain a homogeneous radiation it is necessary to filter it very strongly." Since the apparatus generally used at Erlangen is of Erlangen manufacture the above favourable opinion of the Lilienfeld tube is of importance. During a visit to the Erlangen clinic, the present writer found this tube in use there for deep therapy, and it is similarly used in many of the other German clinics.

The advantage of this tube, stressed by Wintz, as regards homogeneity of radiation, is due to the fact that in the Coolidge type tube any electron

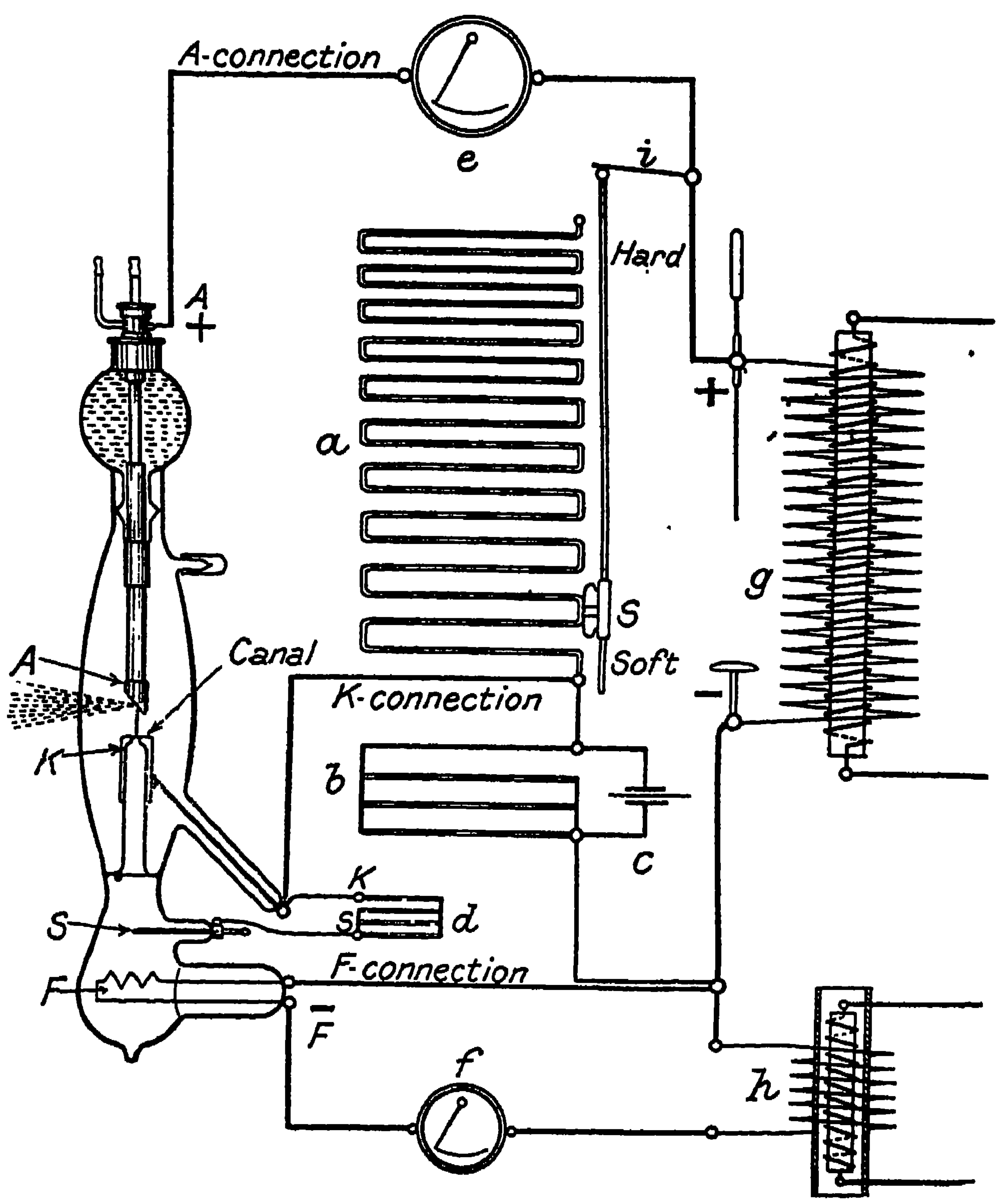



FIG. 133.—Lilienfeld Tube Connections.

emitted by the filament must necessarily pass to the anode whatever the value of the applied potential.

Hence, when the tube is used with alternating current, the lower voltage components of the half cycles are effective in driving these electrons to the target to produce unusefully soft X-radiation, liable to give rise to X-ray burns during long-continued screening operations. We have already indicated how this non-useful radiation may be avoided by use of filters, but such filters must necessarily cause the simultaneous partial uneconomical absorption of the useful hard radiation. Another

method of avoiding this soft component of the radiation is by use of suitably arranged rectifier segments.

This objection is practically the sole physical disadvantage of the two-electrode electron tube as compared to the gas tube, but Lilienfeld succeeded in producing in an electron tube, the advantage of sudden breakdown, as in the gas tube, combined with the advantage of regularity of operation of the electron tube.

The Lilienfeld tube is in England protected by Brit. Patent 23,169/1912 of October 10th, 1911, in which an incandescent coated platinum strip is used as a source of electrons, by Brit. Patent 1,843/1913, in which the electrodes are arranged in order of potential, and by Brit. Patent 4,097/1915 of November 15th, 1913, which is virtually the modern Lilienfeld tube.

Whilst the first-mentioned patent is the first British patent for an electronic tube and is distinguished by the specification of an extremely hard vacuum, such that discharge will not otherwise occur, the use of a hot filament to promote softening and discharge is due independently to Gover and Cooke and to Bonetti. Wehnelt and Trenkle in 1904 * also Dember and Whiddington, used a filament to produce soft X-radiation. The modern form of Lilienfeld tube is shown in Fig. 50 and Fig. 133, and has four electrodes.

Electrons are emitted from an incandescent filament F. This is to be distinguished from the usual fragile X-ray tube filament in that it is a strong tungsten filament of electric light lamp type. It is maintained with a current of 13 amperes at about 5 volts. This filament is not subjected, as in the Coolidge type tube, to the high potential and electrostatic stress, being shielded from this by the electrode K. In some Lilienfeld tubes this filament is within an annexe to the tube and in other forms of experimental Lilienfeld tubes it has been replaced by a mercury vapour arc which both causes electron emission and acts with the cathode K to form a mercury vapour pump to remove any residual gas from the region between the cathode K and anode A.

Electrons from this filament pass to a heavy cathode K, but the rate at which they do so is controlled by means of a rod electrode S, which can be given a variable charge with respect to F and, in consequence, acts like the grid of a triode thermionic valve to repulse and only allow electron emission from F to the "plate" electrode K, at regulated voltages between F and K. This electrode has usually a positive charge with respect to the filament, by connecting it to the cathode K *viâ* a non-inductive resistance *d* of several hundred ohms.

With this electrode arrangement the low velocity electrons emitted from the filament are, by the attraction of the electrode S, given an increased velocity and are therefore available to produce useful X-radiation after their passage *viâ* K. If S is given a negative potential the

* *Ber. d. phys. med. Soc. Erlangen*, 37, p. 312, 1905.

result is that the electron emission from F is decreased by electrostatic repulsion and low velocity electrons are repulsed.

The number of electrons that reach K can therefore be roughly controlled by S and so serves to give the advantage of electron emission at certain regulated speeds rather than a continuous emission at speeds varying from zero upwards, as in the ordinary filament tube. The discharge in consequence, has a definite long wavelength limit and partakes of the nature of the discharge of a gas tube with a definite long wavelength limit due to non-ionisation below a certain critical voltage. The objection of the normal electron tube is thereby overcome.

The electrons released from F and allowed to pass by S, if their velocity is sufficiently great, are caused to pass within a hollow electrode K, by an applied voltage of several thousand volts from an auxiliary transformer known as the "firing" or "trigger" transformer (*Zündtransformator*). Within this hollow electrode, by impact with the metal walls, secondary electrons are given off from the electrode walls. The number of these secondary electrodes and the flow of electrons from F to K are dependent upon the voltage between F to K. In this way the quantity of radiation *viâ* the tube is controlled not by regulation of the current *viâ* and the temperature of the filament F, but by the applied regulated voltage across F to K.

The electrode K, which acts as anode with respect to F and as a cold cathode with respect to the anode A, is provided with a small canal, and under the influence of the main voltage across K and A the electrons pass from without the cathode K to impact upon anode A to excite X-radiation.

Although such a property has never been claimed by Lilienfeld, this tube is also largely self-focussing. The focus is primarily dependent on the size of the hole in K. If a large current is passed *viâ* the tube, this necessitates a high voltage between F and K to increase the electronic supply. The electrode K is then more positive with respect to F than before and the attraction of electrons by the walls of the cylinder is greater, so that the electron beam within broadens, aided by the mutual electronic repulsion. When however the current is small the voltage across F and K is small and K is less positive with respect to F and, as a consequence, negative electrons are less attracted by the cylinder walls and the electron beam narrows in diameter to give a low current value sharply focussed discharge.

The anode A is of platinum and is efficiently water-cooled by circulating water. In consequence a high current output is obtained up to as high as 150 milliamperes. Further this high current is increased by the use of 500-cycle alternating current, of which only uni-directional halves of the cycle are applied to the X-ray-tube. So 500 X-radiation impulses per second are given to the tube, instead of only 100 to 200 with the more

usual electron tube, which is limited in energy passage by the fragility of its cathode filament.

The intensity of the X-radiation with the Lilienfeld tube is therefore very great, as may be appreciated from Fig. 134, where the intensity is represented in the case of the Lilienfeld tube by curve A and in the case of a German Coolidge type tube by curve B. The latter tube would however appear to give a shorter wavelength limit from these curves, (published by the Lilienfeld tube manufacturers to show the greater homogeneity of the Lilienfeld tube radiation).

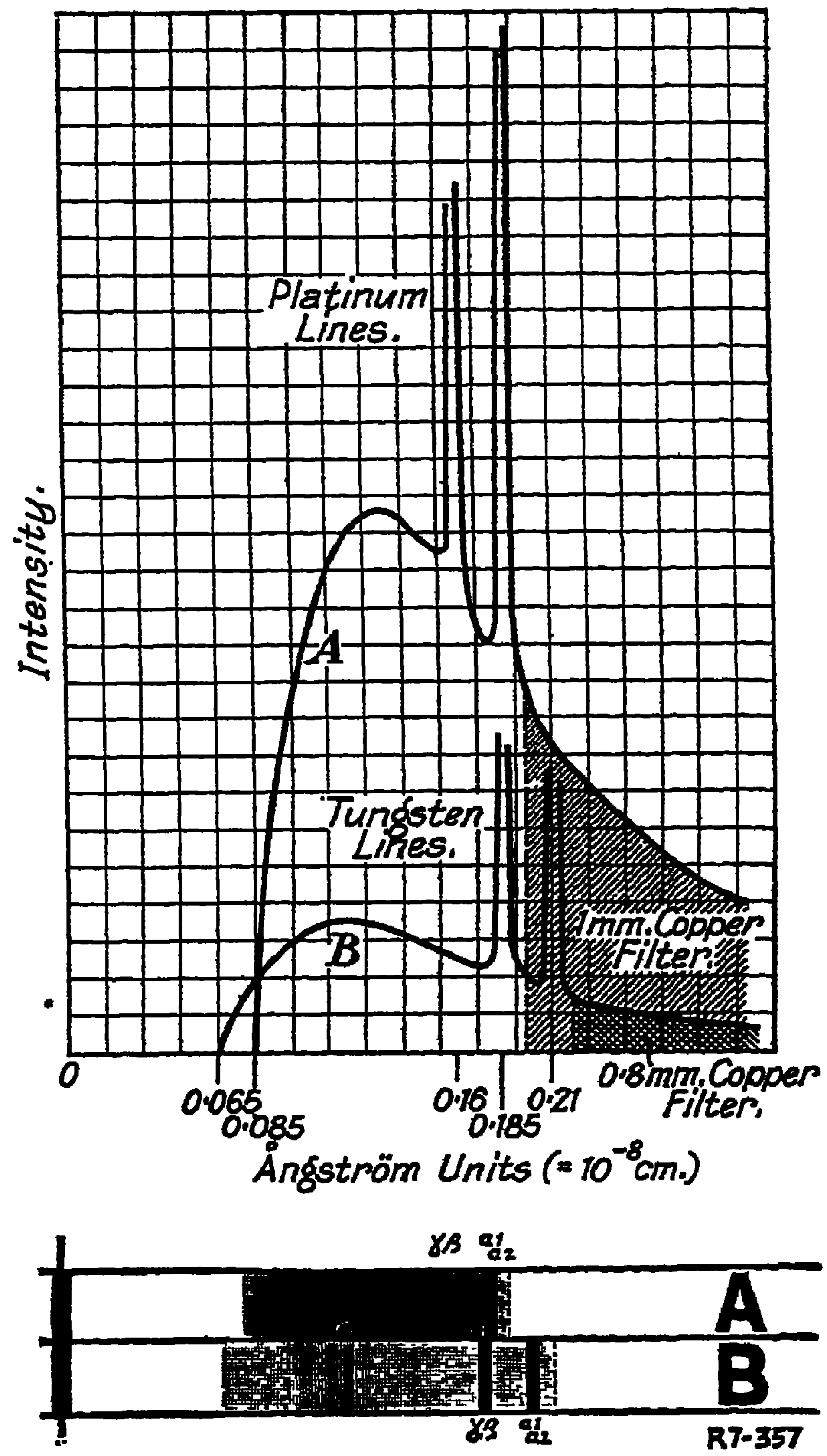



FIG. 134.—Comparison of Coolidge and Lilienfeld tube emission.
A. Lilienfeld tube. B. Coolidge tube.

The advantages of the Lilienfeld tube as compared to the more common type of electron tube may therefore be summarised as;

(1) Greater homogeneity of radiation.

(2) Greater output due to very efficient cooling and use of 500 impulses per second as compared to 100 with the normal electron tube.

(3) Use of a protected filament which does not directly control the intensity, but is of such dimensions that a very large electronic current and tube output can be obtained.

(4) The cylindrical electrode has self-focussing properties.

Against the Lilienfeld tube is the greater complexity of the circuits, but this is more a theoretical than a practical objection, since it is as equally convenient to alter the potential between K and S as to alter the filament current to F, and once the voltage of the electrode S is fixed (which is only occasional) the variation of intensity and quality only involves two operations as in the case of the normal type electron tube.

A more sound criticism than the usual criticism of complexity of circuits as regards operation would be that the introduction of the additional electrodes is more likely to cause the X-ray tube to act as a valve

oscillator and so to produce high-frequency currents very dangerous to the insulation of the transformer. Practice however shows such an effect to be negligible, installations utilising such tubes having operated over many years without breakdown. It is to be regretted the tube has not more greatly been used in England.

Langmuir * has alleged that the original Lilienfeld tube (predating the work of Langmuir which resulted in the Coolidge tube) was not of high vacuum, since the current *viâ* the tube did not vary as the 1·5 power of the voltage as found by Langmuir's experiments. Lilienfeld † has shown that this relation varies in different tubes in which there can be no question of poor vacuum, and is apparently dependent upon other factors, as the relations of electrodes to each other and the tube walls. Dauvillier ‡ states Langmuir's assertion can, in view of these later experiments of Lilienfeld, no longer be justified. Lilienfeld would appear in his earlier writings upon his tubes to have misinterpreted his theoretical results rather than to have failed in the practical production of an efficient electron tube.

## THE AUTO-ELECTRONIC TUBE

Of recent years Lilienfeld § has produced a new tube which is dependent upon what he terms the " auto-electronic " effect and which permits the production of a purely electronic discharge without the use of a heated filament.

We may consider in the case of a metal filament that the absorption of heat energy, results in the transference of atomic electrons from orbits nearer to the positive atomic nucleus to more distant orbits of greater energy value. Since the weak attraction of such distant electrons by the positive nucleus is so still further weakened, such elections are virtually " free-electrons " upon which normal electrical conduction is dependent and, if situated in an intense electric field as between the electrodes of an X-ray tube, they will be drawn towards the anode and so constitute a current *viâ* the tube.

It is doubtless such free electrons which are responsible for the thermionic effect as well as for the photo-electric effect, *i.e.*, in the first case they obtain from the applied heat energy sufficient energy to allow them to leave the boundaries of the solid by overcoming the positive nuclear attraction and, in the second case, they obtain such energy from the energy of the incident radiation.

The thermionic effect is also a purely relative effect, *i.e.*, a cathode at normal temperatures has considerable temperature if we consider it in

* *Phys. Rev.*, 11, 1913.
† *Ann. der Phys.*, 61, p. 221, 1920.
‡ " La Technique des Rayons X," p. 72.
§ *Verh. der deut. Phys. Ges.*, 2, p. 13, 1921. *Phys. Zeits.*, 23, p. 506, 1922. *Amer. Jour. of Rönt.*, 9, p. 172, 1922.

relation to absolute zero temperature ($-273°$ C.) instead of from the common temperature scale. There must therefore, in all cold electrodes, be a certain proclivity to the thermic emission of electrons.

Under normal conditions the forces retaining the electrons to the atomic nucleus are sufficiently great to prevent the escape of electrons. If however we heat the cathode, or, under certain conditions submit it to ultra-violet radiation, the electrons will obtain sufficient kinetic energy to escape from the nuclear attraction.

Even without these means of causing the electrons to be released from the positive nuclear attraction it should be theoretically possible to cause the removal of the electrons if we can apply a sufficiently great electrical field.

We know, in the case of the electrodes of the normal heated filament electron tubes, that no electronic emission results when the potential difference is applied to the tube with the cathode cold.

Taking the voltages used in such tubes as the practical limits of voltage we have therefore to adopt other methods of increasing the electrostatic field.

In discussing the phenomenon of brush discharge (Vol. I.) we have stated that brush discharge, or conduction, occurs more readily from an abruptly curved surface as a wire, than it does from a less abruptly curved surface as a tube of wide bore, since the electrostatic tubes of force are much more closely approximated at the periphery of the wire than at the periphery of the tube.

If therefore our practical voltage is not sufficient it should be possible to increase the action of such voltage by utilising a surface of large curvature, as a wire or point.

Earhart and Hobbs,* during 1901 to 1908, by delicate interference methods were able to show with very pointed electrodes in air, at distances of 0 to $3\mu$, a discharge could occur which was independent of the intervening gas and the electrons were apparently derived from the metal of the electrodes.

Hoffmann† during 1910 to 1917 with a specially delicate electrometer arrived at similar results.

Millikan‡ also obtained results which tended to show that at very high electrostatic densities such a discharge could result.

Schottky investigated the subject from the theoretical aspects.

To Lilienfeld is due the credit of first conceiving that such a discharge might, in a vacuum tube, be a source of X-radiation, and he obtained positive results by ;

* Earhart, *Phil. Mag.*, 1, p. 147, 1901 ; 16 p. 48, 1908. Hobbs, *Phil. Mag.*, 10, p. 617, 1905.

† Hoffmann, *Phys. Zeits.*, 11, p. 961, 1910 ; 13, pp. 480, 1029, 1913. *Ann. der Phys.*, 42, p. 1196, 1913 ; 52, p. 665, 1917. *Verh. der deut. Phys. Ges.*, 12, p. 880, 1910.

‡ Millikan, *Phys. Rev.*, 12, p. 167, 1918 ; 15, p. 239, 1920 ; 27, p. 51, 192?

(1) The use of very pointed electrodes, having the effect of concentrating the electrostatic stress upon a point of the cathode.

(2) Assisting this increase of stress by close approximation of the electrodes.

Millikan* has more recently produced a similar auto-electronic discharge by use of an axial wire of ·00123 cm. diameter within a cylinder of 1·625 cm. diameter. Millikan estimated that in such an arrangement the electrostatic field at the periphery of the axial wire exerts a force 228 times the applied potential difference, *i.e.*, 228 times the force upon a plane electrode.

According to Lilienfeld's conception of this auto-electronic phenomenon, the loss of such electrons from the cathode surface should result in a lowering of cathode temperature in much the same way that molecular evaporation from a liquid causes a lowering of temperature of the liquid. Lilienfeld has been unable to demonstrate experimentally such a temperature variation and the auto-electronic effect appears to be independent of the electrode temperature, a result also obtained by Millikan and the General Electric Company Research Staff† (London) and which tends to show the emission of electrons in the auto-electric effect is not purely a thermionic effect. Millikan believes the electrons are the free electrons of the metal of the electrode and these are removed from minute protuberances or irregularities of the surface. Such removal is greatly affected by the treatment of the metal, for example if this is heated, the effect is much smaller apparently owing to chemical action, as oxidation, rounding off such irregularities.

To the writer the view that a temperature decrease should result as in molecular evaporation does not appear to be necessarily correct. In the case of a liquid, if the external pressure is removed, the molecules can only obtain the necessary energy of evaporation from the liquid, which therefore suffers a temperature fall unless heat is applied.

In the electronic case however the energy of extraction is obtained from the energy of the electrostatic field and not necessarily from the cathode, which may, in consequence, not suffer the reduction of temperature sought by Lilienfeld.

The auto-electronic discharge must be somewhat analogous to the abrupt discharge of the gas tube rather than the continuous discharge of the heated filament thermionic tube.

This follows since there would be a certain (average) value of nuclear attraction upon the " free " electrons and their release could not occur until this critical value is abruptly overcome by the attractive electrostatic field. Unlike the thermionic tube, the emission of X-radiation due to such electrons would be very homogeneous.

* Millikan, *Phys. Rev.*, 27, p. 51, 1926.

† The Research Staff of the General Electric Company, London (*Phil. Mag.*, 1, p. 609, 1926) have obtained auto-electronic currents as high as $10^{-2}$ amperes, *i.e.*, of the order of one hundred milliamperes.

In the tubes as used by Lilienfeld, which he terms the *Aonröhre*, the electrodes may be approximated as closely as 10 mm. The cathode is pointed, so having a very small radius of curvature, and the voltage necessary to cause discharge is found to be proportional to this radius. If other surfaces are within the neighbourhood, the voltage required is increased, as would be expected, since such a surface would be expected to modify and necessarily decrease the field in the region of the pointed cathode.

The anode is a cavity of about 5 mm. diameter and 4 mm. depth. The use of such a cavity apparently prevented arcing. The metals used for electrodes are highly refractory metals, as tungsten, tantalium, or molybdenum, partly to aid extreme heating of the electrodes during exhaustion and further that the atomic electrons are so firmly held by the atomic nuclei, that considerable energy values of at least 5,000 volts and usually 40 to 50 kv. are necessary for their removal, in order to give useful X-radiation when the freed electrons collide with the anode electrode. Lilienfeld states that with calcium, a metal of low atomic weight and nuclear attraction, the effect can be produced at a distance of 1 mm. with only a few hundred volts.

The vacuum must be extremely higher than that with the hot cathode tube, and to effect this, Lilienfeld seals into an annexe to the tube accessory electrodes, the anode of which is easily volatilised. After sealing, these electrodes are volatilised by discharge and the resulting finely divided metal is said to decrease by occlusion the vacuum to four or five times the sealing-off value. These tubes, in consequence, utilise the highest vacua yet reached and any variation is stated to greatly influence their operation. Currents of 5 milliamperes and above have been produced at 100 kv. and the tube is self-rectifying.

X-radiation is given out from the anode and also to a small extent from the cathode, which also emits light radiation. Lilienfeld states that whereas the wavelength of the emitted radiation decreases with increase of voltage, the effect is independent of temperature, a statement, in view of the co-existence of thermionic emission, open to question. Also the electrons are said not to take a straight-line course between the cathode to anode but to follow a curved course of some centimetres. The "focus" of the tube depends upon the curvature of the anode cavity, and Lilienfeld has constructed tubes having double anodes, *i.e.*, two cavities acting in conjunction with a single cathode, in order to give bifocal tubes.

It is stated that after long-continued operation of such tubes there is no change in the electrodes, even after operation for some hundreds of hours at 10 milliamperes.

The weak point of these tubes appears to be in the sharp dependence of the effect upon the inter-electrode distances, and in his patent specifi-

cation (Brit. Patent 155,554/(1919) Lilienfeld shows various means of regulating this distance.

In Fig. 135 (1) the distance between the point electrodes is varied by the expansion of a conductor H heated by electricity. In Fig. (2) this distance is adjusted by the actual compression of the glass F by clamps G, a procedure which would appear to be associated with some risk.

In Fig. 135 (3) the movement is effected by movement of an internal armature J, under the action of an external solenoid M and control of a spring L. To prevent the armature J disengaging gas it is sealed within a glass cylinder K.

In Fig. 135 (4) the tube is made in analogous construction to the more common Lilienfeld thermionic tube. An accessory electrode C is mounted, secured by rings of quartz Q, in a hollow cathode B, and electrons, set free from C, may be focussed upon the sleeve J. Discharge between B and C is commenced by the firing transformer Z, and the electrons so evolved are driven against the target D, by the potential of the main transformer R. In this case the potential of Z between C and B determines the quantity of radiation and of R between B and D the quality of radiation as in the thermionic Lilienfeld tube.

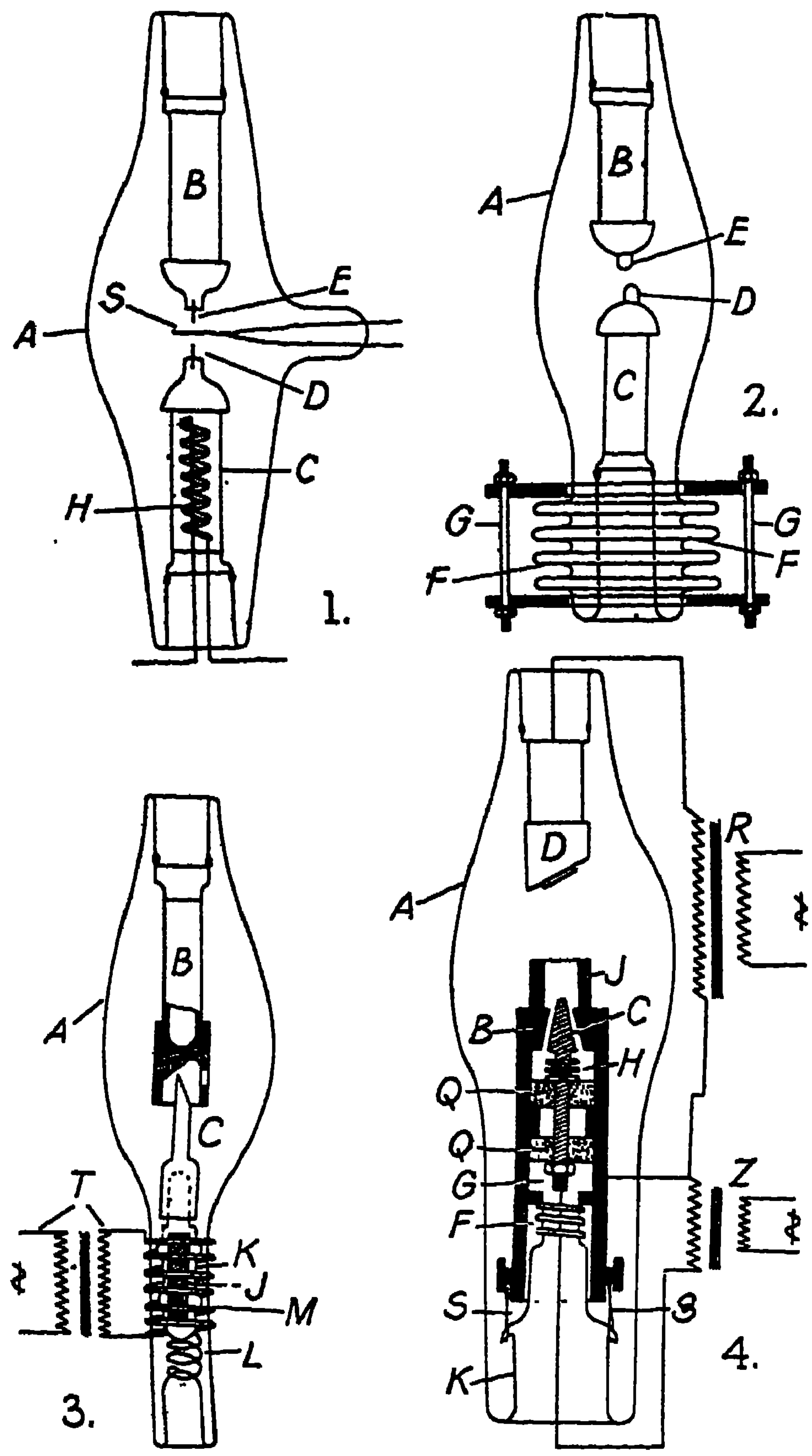


FIG. 135.—Lilienfeld Auto-electronic Tube.

The auto-electronic phenomenon is also applied by Lilienfeld for the generation of high-frequency oscillations, by means of triode auto-electronic valves.

Various accessory electrodes, for example S (Fig. 135 (1)); maybe introduced to heat the electrodes by bombardment during evacuation, and are afterwards removed by various ingenious devices.

This type of tube appears to be capable of much promise, particularly for very deep therapy tubes, but no accounts have appeared of the

Lilienfeld auto-electronic tube as regards clinical results, although statements of such use have been made.

It appears to be still awaiting development on the part of Lilienfeld. That such an effect occurs is most definite in view of the further experiments of Millikan and the General Electric Company, London. Also the Research Staff at the Royal Arsenal Laboratory in a patent (Brit. Patent 246,194/1925) adopt means in the normal thermionic tube to prevent this auto-electronic effect by giving the electrodes a rounded edge.

Müller (Brit. Patent 191,749/1922) has also protected a particular form of electrode for an auto-electronic tube as a result of earlier experiments, and, in a personal letter to the writer, states; "This patent has not up to the present found any application, since the manufacture of such tubes offers very great difficulties. My present view is that it is not unlikely that the principle will obtain importance. This naturally supposes that these difficulties are overcome."

## METAL X-RADIATION TUBES

Whilst during the past few years the high-tension apparatus for X-radiation excitation has shown a tendency to pass from laboratory standards to engineering standards, the weak link for high power is still the X-ray tube, by virtue of its glass construction with mechanical and expansile fragility. The use of silica having greater resistance to fracture by uneven expansion is of distinct value, but suffers from the fact the silica is a bad heat conductor and does not easily allow electrodes to be sealed in.

Hence, whereas it is nowadays easily possible to obtain voltages of 1,000,000 volts or more, the application of such voltages to X-ray purposes is limited to, at the most, the use of 300 kv.

Exactly the same condition of affairs occurred during the development of power triode valves for wireless and other purposes at a later date. These were originally of small output and subject to great irregularities, whilst they were still a laboratory construction, but, in the hands of the larger engineering companies, silica and metal valves, capable of dealing with very high voltages and amounts of energy as high as 1,000 kw. (the Magnetron), have been successfully produced.

Now that the manufacture of X-radiation tubes has been seriously taken up by some of the larger electrical companies, we may look forward to the rapid development of metal X-radiation tubes of large output.

It is only within the last two years that any form of practical commercial metal X-ray tube has been produced, and its use, whilst increasing, is by no means yet general.

Whilst the purely medical reader usually considers such metal tubes

to be a very recent development, like many other X-radiation innovations, the production of a metal X-ray tube is a very old experiment, the first metal tube known to the writer being that of B. Davis produced and used in 1896, *i.e.*, within a year of Röntgen's discovery of X-radiation.

Considering the fragility of the universal glass X-ray tube, even with the most careful handling and its liability to fracture by practically uncontrollable causes, as cold draughts playing upon a heated tube, it is surprising that this very early indication of Davis was not pursued much earlier, except in the domain of physical research, where many metal tubes have been successfully produced and operated.

Given the possibility of constructing a metal envelope tube with suitable insulation, we have at once the following advantages ;—

(1) Little risk of accidental mechanical damage, as occurs with glass envelopes.

(2) The blowing of a glass bulb is in practice limited in size. This limits the voltage and power at which glass tubes can be operated, and this, in turn, the penetration and intensity of radiation respectively. With metal tubes no such limitations arise.

(3) Cooling is facilitated with metal tubes as the risk of fracture by uneven expansion is small in comparison to the risk with glass. Such cooling also allows the metal X-ray tube to be a more efficient X-ray generator than the glass tube, *i.e.*, the percentage of energy converted to X-radiation energy is increased.

(4) Great protection against non-useful injurious stray radiation, since the metal envelope can be made thick to absorb all emitted radiation except in a given desired direction.

(5) Greater economy of accessory apparatus in view of (4). As the area of protection required to absorb radiation varies as the square of the distance from the source and, as such protection must necessarily be distant in the case of a glass X-ray tube, in the latter case there is an enormous weight of protection necessary. The need of movement of the X-ray tube and its protection, in turn necessitates heavy counter-weights and complicated mechanical arrangements, with consequent cost. The use of a metal tube, where adequate protection is obtained with comparatively negligible weight of protection, immediately simplifies and cheapens all X-ray apparatus with the added advantage of economy of space.

(6) The small size of the metal X-ray tube, as compared to the glass tube plus its protective box, allows more easy and greater range of mechanical movements. For example, in practice the tube box movement of the usual couch is practically always restricted to a horizontal longitudinal and transverse movement, but with a small metal tube oblique movements in the vertical planes can be easily obtained, whereas the size of the normal large tube box prohibits these.

(7) Less risk of danger to patient or operator, since the danger of fracture and implosion is removed.

(8) No risk of electrical shock to patient or operator due to contact, since the metal container can, if necessary, be earthed and so rendered shock free.

(9) The size of radiation field can be more effectively controlled and concentrated to a smaller area. Such an advantage is of great importance in " cross-fire " deep therapy, as the number of ports of entry to a deep-seated tumour can be increased with greater safety.

(10) When a tube fails in operation, for example, in consequence of the burn-out of the filament, the repair can be quite simply and quickly carried out, this being actually already done in many physical applications of X-ray tubes. Doubtless the tube of the future will be a metal tube easily dissembled in permanent connection to a vacuum pump, with means to vary the degree of vacuum to any desired value.

(11) The metallic structure more readily allows the rapid introduction of more suitable targets such as those capable of movement (p. 114), in order to promote better heat distribution and greater radiation efficiency to an extent impossible in a glass X-ray tube. A patent already exists (Brit. Patent 243,310/1925) in which a metallic iris diaphragm is directly inserted within the tube, instead, as is more usual, outside the tube. This foreshadows the possibility of practical movement of the target actually within the tube (see Appendix II.).

(12) It is more easy to obtain, with a metal X-ray tube, the radiation in the direction of the electron stream. Such directioned radiation is well known to be more intense and of superior average quality to that omitted from the oblique target of the glass X-ray tube. In the glass tube the danger of utilising such radiation is largely the risk of fracture due to unequal expansion of the bulb in the region of the junction of the bulb and cathode neck.

One may say, given a suitable and practicable metal X-ray tube, it is in all respects preferable to the glass tube. The only objections to the metal tube are constructional disadvantages, all capable of being overcome, namely ;

(1) The difficulty of making satisfactory glass and metal seals (see p. 53).

(2) The risk of fracture at such seals due to ionic bombardment (see p. 54), unless such seals are suitably protected.

(3) The difficulties of exhaustion, due to the metal disengaging gases. This difficulty is overcome by strongly heating the metal *in vacuo* prior to its use, and any oxide present upon its surface is removed by repeated emission and pumping off of hydrogen, which reduces the oxide. The resulting water is driven off by heating the metal and then pumped off.

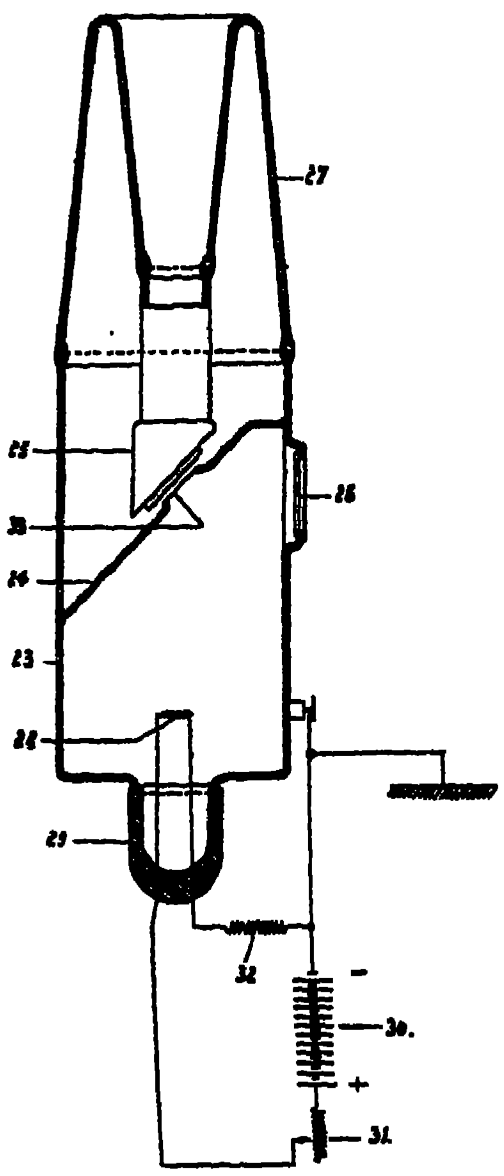


FIG. 136.—Device to Prevent Space-charge in Metal Tubes (Messrs. Philips Lamps, Ltd.).

(4) More important than the above is the tendency for the metal container to emit characteristic radiation of the metal under stray electronic bombardment. This objection can be overcome by suitable design, so that stray electron paths do not exist and all electrons pass to the target only.

(5) The space charge (*q.v.*, p. 225, Vol. I.), is large in metal tubes and tends when the tube is worked at low voltages (for physical purposes) to prevent further electron evaporation from the filament by the repulsive effect of the charged walls. This may be overcome by the use of a less degree of evacuation so that residual gas ions are present to neutralise the space-and-wall charge. This method results however in filament bombardment and destruction.

A better method is to render the metallic wall 23 (Fig. 136) at a greater negative potential than the filament, by use of a suitably disposed resistance 32. The negatively charged wall then tends to prevent the growth of space charge, by repulsion of electrons towards the centre of the tube between cathode and anode, where they are more subject to the intense potential field between these electrodes.

## PRACTICAL METAL TUBES

As already mentioned, the first metal tube was produced in March, 1896, by B. Davis,* a pupil of Lodge.

The success of this early tube may be judged when Davis states his tube was able to transmit rays *viâ* 3 ft. of timber and allowed the bones of the hand to be seen on a fluorescent screen at a distance of 30 ft. and even 62 ft., facts which compare very favourably indeed with the inefficient glass tubes of this date.

One example of Davis's tube is shown in Fig. 137, and consisted of a copper stem carrying a platinum anode. Most remarkable is that various shields were used to surround this anode, some of which are identical with the cylindrical and flat shields revived at a later date to surround the filament of the electron tube. The action of these shields was to concentrate and to focus the (at this date unknown) electrons on the target just before their point of impact rather than at their point of

* *Nature*, 54.p. 281, July 23rd, 1896. Röntgen Societies Exhibit No. 57.

origin as in the electron tube. Davis particularly stresses the importance of such shield variations.

The anode stem was insulated by means of an ebonite sleeve and the

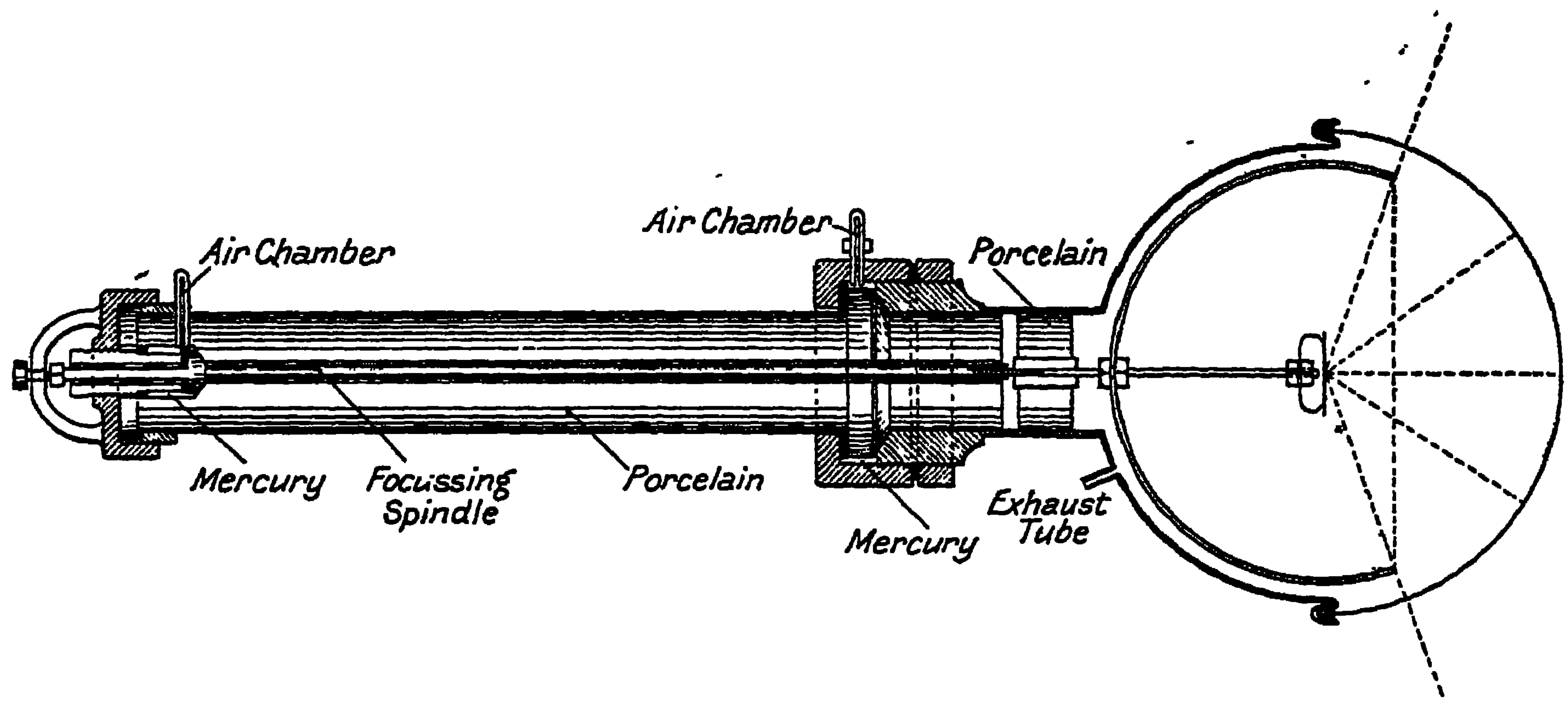



FIG. 137.—Davis Metal Tube (1896).

cathode formed of a sphere of aluminium or copper, having the anode at its centre.

Whilst the tube would retain its vacuum if not used, on use changes at the rubber joints occurred, resulting in gases being disengaged, and the vacuum was lost within half an hour.

This was overcome by making the joints by means of mercury baths, as shown in the figure. The anode was also made so that its position could be varied, whilst the tube was in use, in order to alter the focus.

In spite of the comparative success of the Davis tube the possibility of utilising a metal tube appears to have been lost to view until 1908, when Lindemann (Brit. Patent 4,479/1908) protected a metal tube shown in Fig. 138. In this metal tube the body was of copper or aluminium with a window of non-absorbent lithium glass (Lindemann glass). On the inclined wall arranged at 45 degrees to the axis was a film of metal of high atomic weight T, as lead, bismuth or platinum, to form the anticathode on which

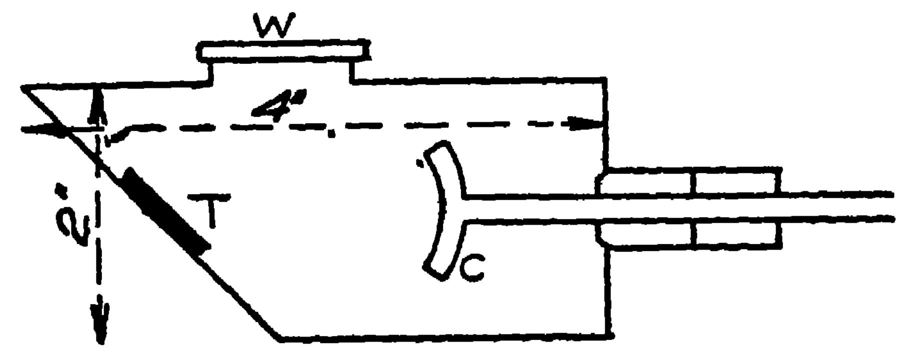



FIG. 138.—Lindemann's Metal Tube.

rays from the concave cathode C converged. Evacuation took place through a special tube sealed or soldered to the apparatus and through the orifice of which the cathode was inserted. No particulars have been found by the author as regards the practical operation of this tube.

Siegbahn,* to whom we owe our most exact physical measurements of X-ray spectra, has designed a metal tube (Fig. 139) to permit the metal of the anticathode to be exchanged easily for such purposes. This can only be carried out in glass tubes by complicated magnetic devices. This tube employs a tungsten filament within a cylindrical cathode. Only

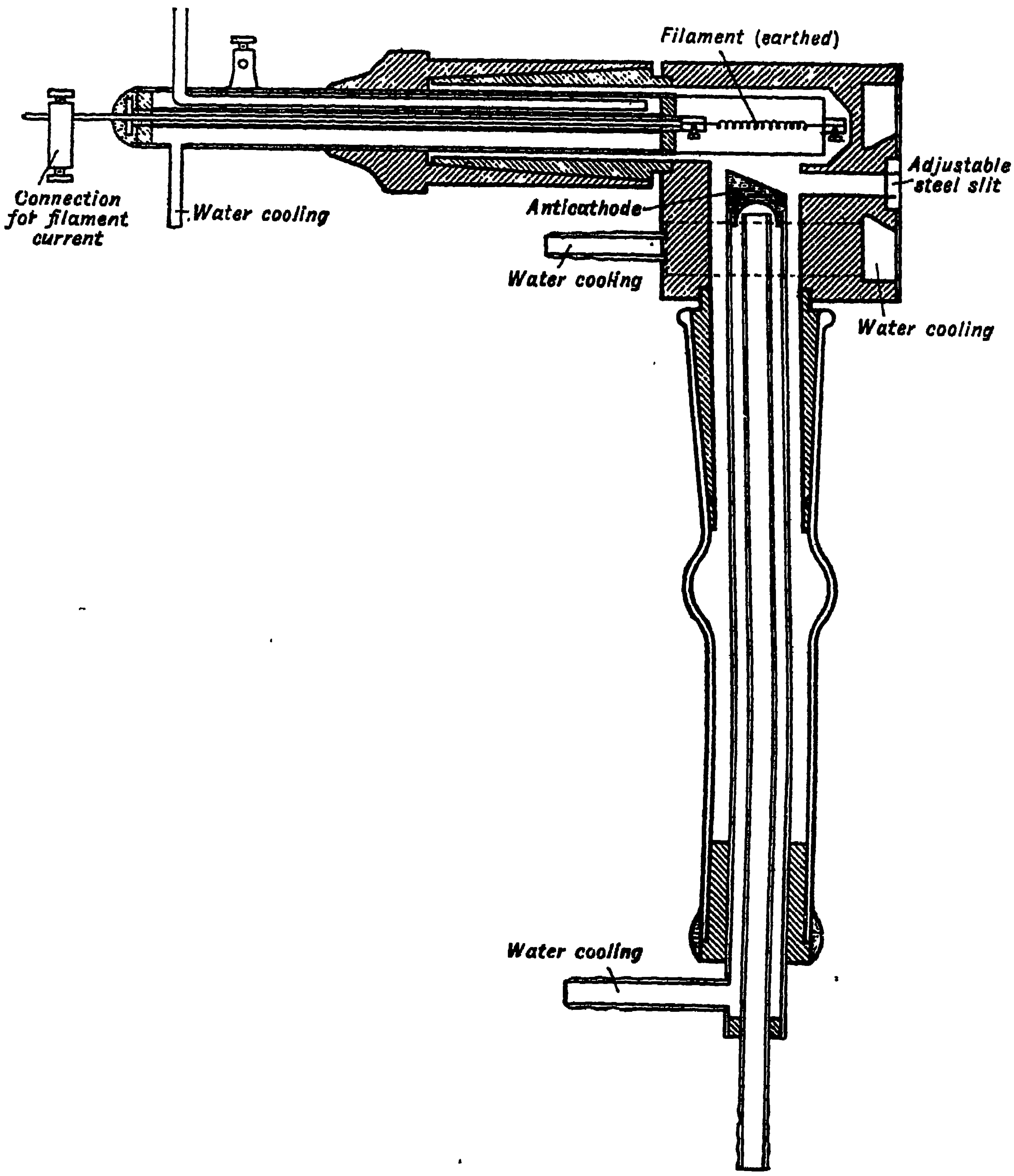



FIG. 139.—Siegbahn's Metal Tube.

the anticathode is insulated by means of a glass tube. Both electrodes can be easily removed and replaced.

Arrangements are made to screw the cathode in or out in order to alter the cathodic focus, which can be so varied from a focus upon the target of a 1 mm. diameter to a focus covering the whole of the target

* *Zeits. f. Phys.*, 9, p. 68, 1921.

face. All the electrodes are water-cooled and the tube could, for spectrographic measurements, run continuously for 10 to 15 hours, with currents as high as 100 milliamperes and voltages of 40 to 50 kv., *i.e.*, over the lower range of medical diagnostic voltages, but with much higher currents

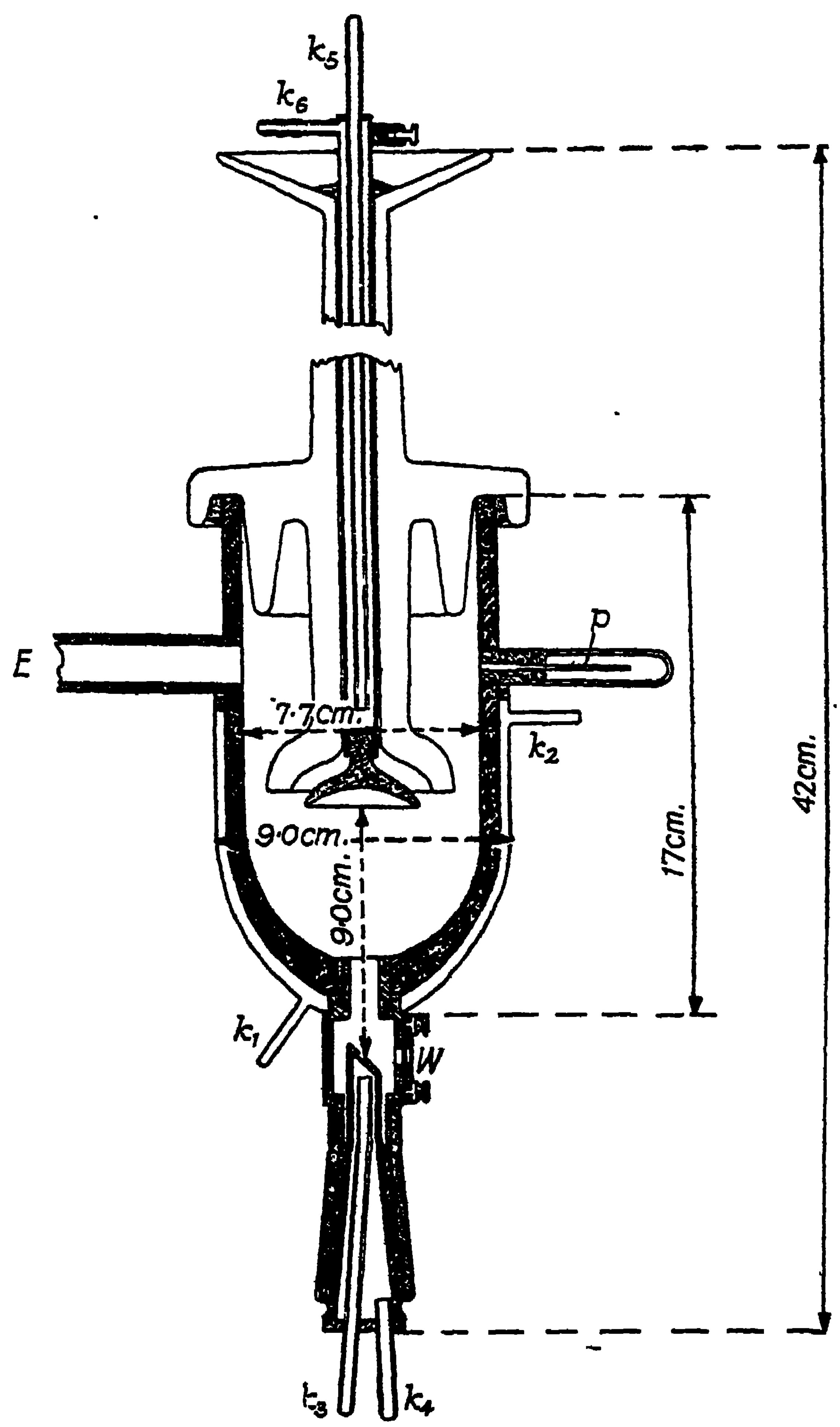



Fig. 140.—Hadding's Metal Tube.

than commonly used in medical work. A somewhat different metal tube has also been described by Siegbahn.*

Hadding,† a pupil of Siegbahn, has also described a metal tube (Fig. 140), in which the use of glass for insulation has been abandoned in favour of porcelain. The tube body is bomb-shaped, and has at the pointed end a

* *Verh. d. deut. Phys. Ges.*, 17, p. 469, 1915.
† *Zeits. f. Phys.*, 3, 369, 1920.

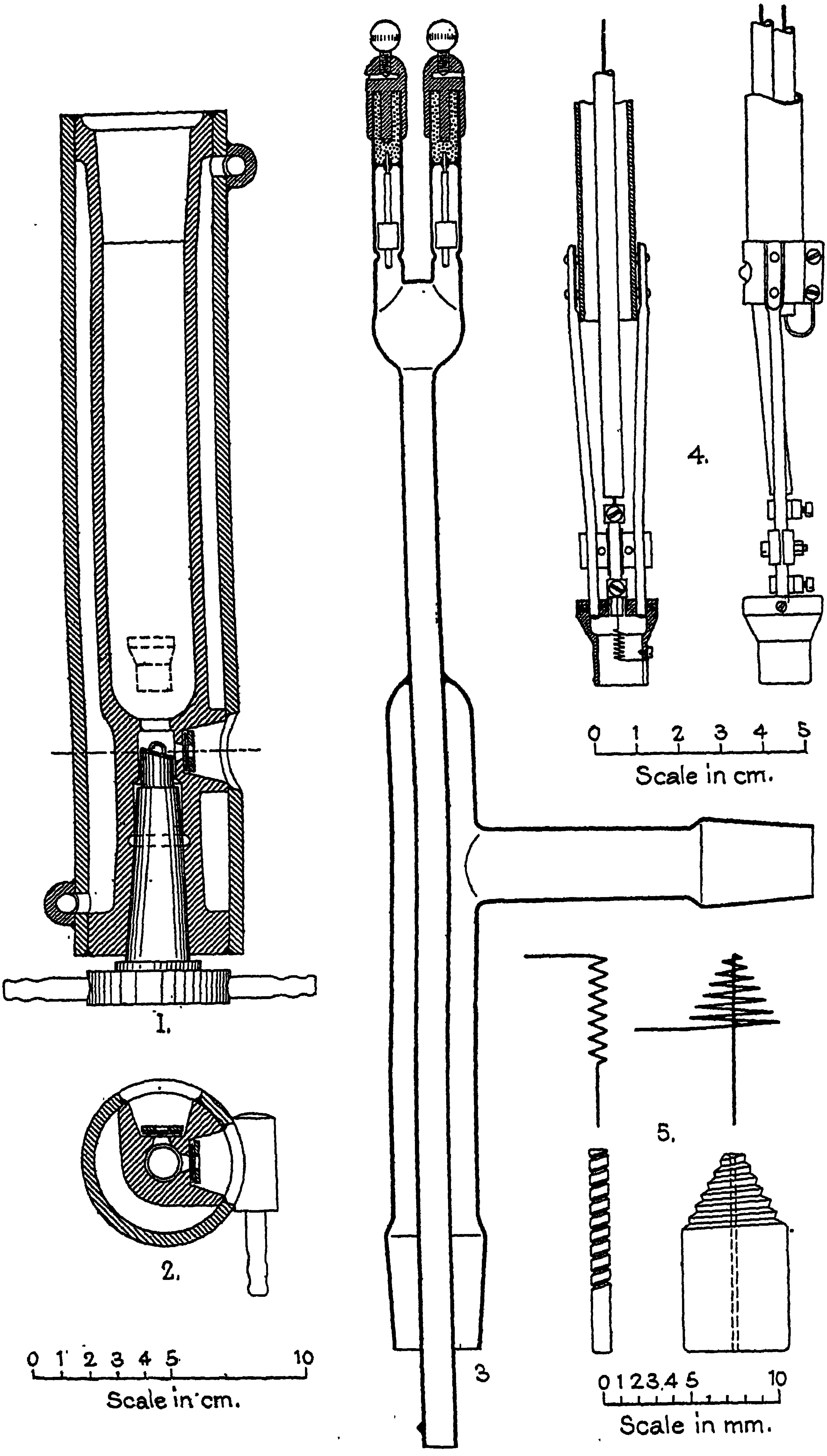



FIG. 141.—Wever's Metal Tube.

conical copper anticathode, water-cooled, *viâ* the tubes $k_3$ and $k_4$. For spectrographic purposes the anticathode is easily exchanged. The radiation is given out from a window W of aluminium foil, screwed down to the tube upon an air-tight layer of adhesive. This window is oval, of diameter 3 × 5 mm. and is aligned upon the focal spot. The cathode is hemispherical to give a sharp focus, and the leads, for a filamentary cathode are within a long high-tension insulator, arrangements being made for water cooling *viâ* ducts $k_5$ and $k_6$. This insulator is cemented to the body by means of shellac. A palladium tube $p$ is present, within a hydrogen chamber, which allows the gas pressure to be varied, but the tube chamber is also maintained in permanent connection to a molecular vacuum pump *viâ* E. The dimensions of the tube are such as to permit the use of a current of 10 to 20 milliamperes at 34 to 37 kv. At 40 kv. the discharge occurs around and not *viâ* the tube. The exposure times for spectrographic work are from fifteen to forty-five minutes.

Wever * has used a tube (Fig. 141), in which the anode is formed of a lead chamber which can be water-cooled and the target can be moved along the long axis, by means shown in the figure. Radiation from this target is emitted *viâ* one or more windows, two being seen in the cross-section shown. The construction of the anode chamber of thick lead ensures no radiation emerges except *viâ* the windows, and it has been found, with efficient water-cooling, there is no tendency for the lead walls to melt. The tube is for physical purposes, the anticathode being interchangeable, iron, copper, palladium and molybdenum having been actually used.

The filament cathode has its leads within the glass insulator shown, which is luted to the lead anode chamber. This tube is so constructed as to allow exhaustion by permanent connection to a pump. The difficulty of insulating the metal and glass portions is overcome by having the anode chamber very long and the filament suspended within this, distant from the glass-and-metal joint. Since such a cathode would be very liable to movement with resulting alteration in position of the cathode stream upon the target, the cathode is supported upon an insulating arrangement which closely fits the tube and so prevents swaying. The method of winding the filament and its insertion into a reflector is evident from the diagram (Fig. 141 (4)). It is stated a new filament can be inserted and the vessel re-exhausted within an hour. The tube works at 45 to 50 kv. with 10 to 20 milliamperes.

Dr. Shearer in England has designed, in collaboration with Dr. A. Müller, various metal X-ray tubes (Fig. 142) for X-radiation research upon organic bodies constitutions. These tubes, as demonstrated by Dr. Shearer to the present writer, are very efficient and simple in operation.

* *Zeits. f. Phys.*, 14, 410, 1923.

They were originally high-vacua electronic tubes, but, owing to difficulties in connection with space charge, it was found their operation is more

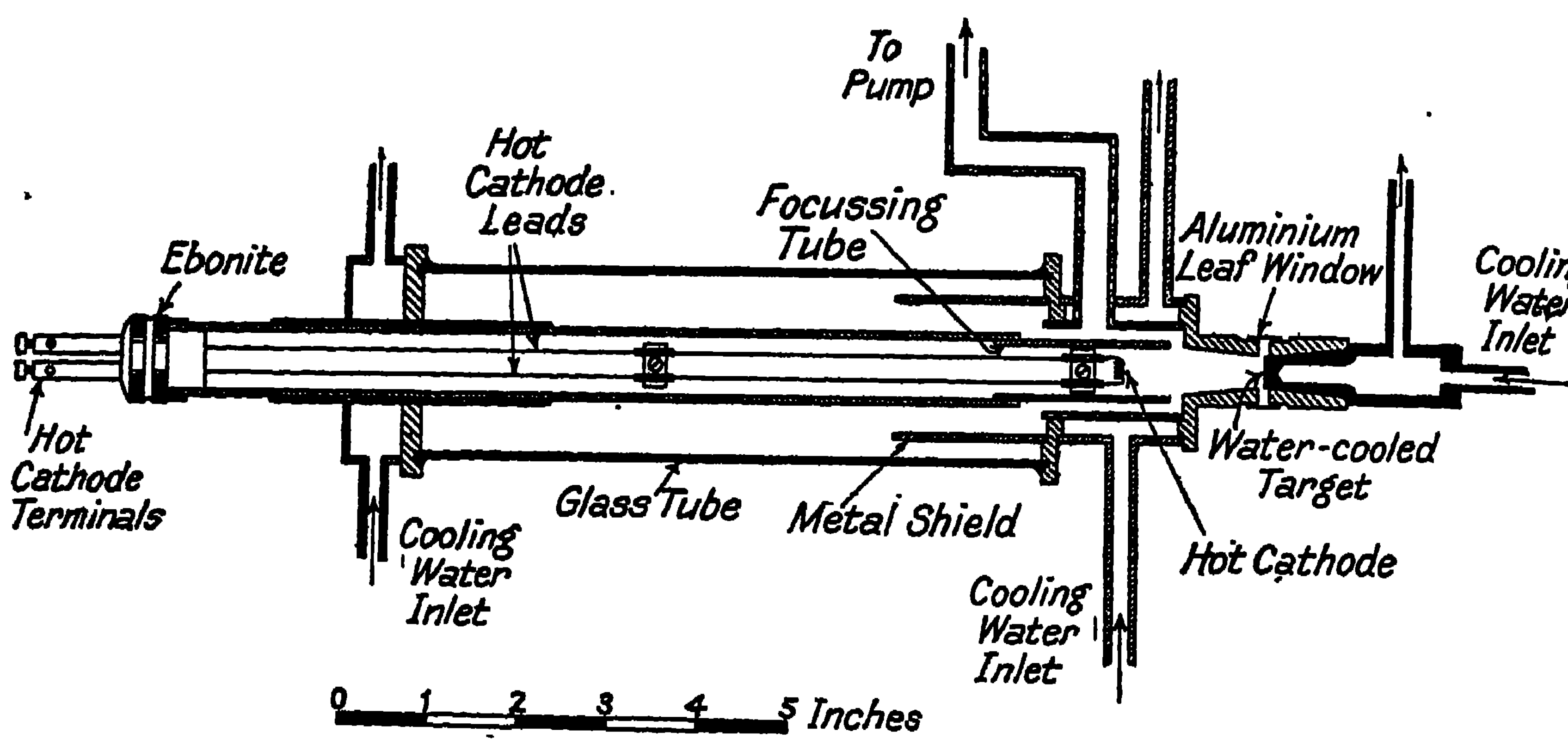



FIG. 142.—Shearer's Metal Tube.

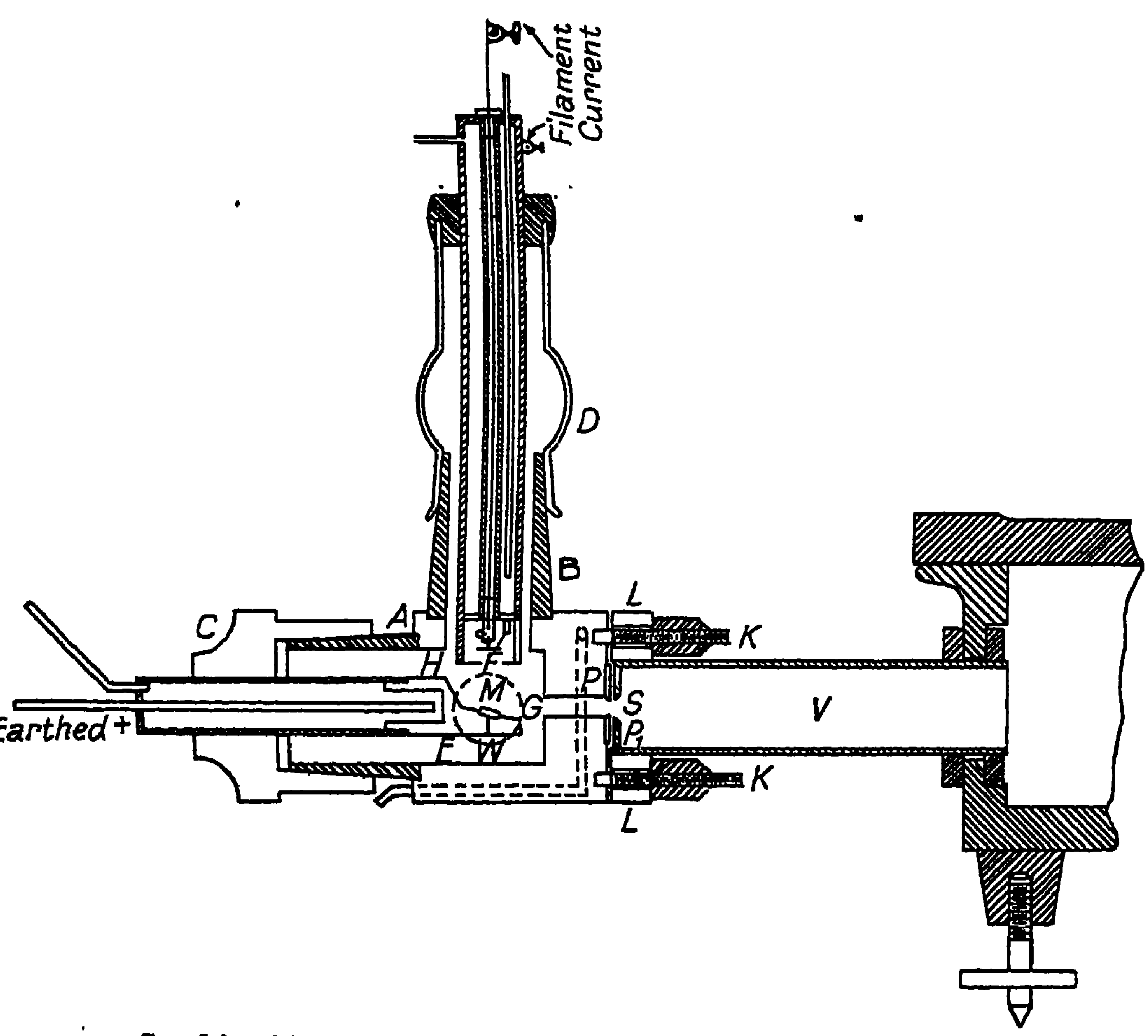
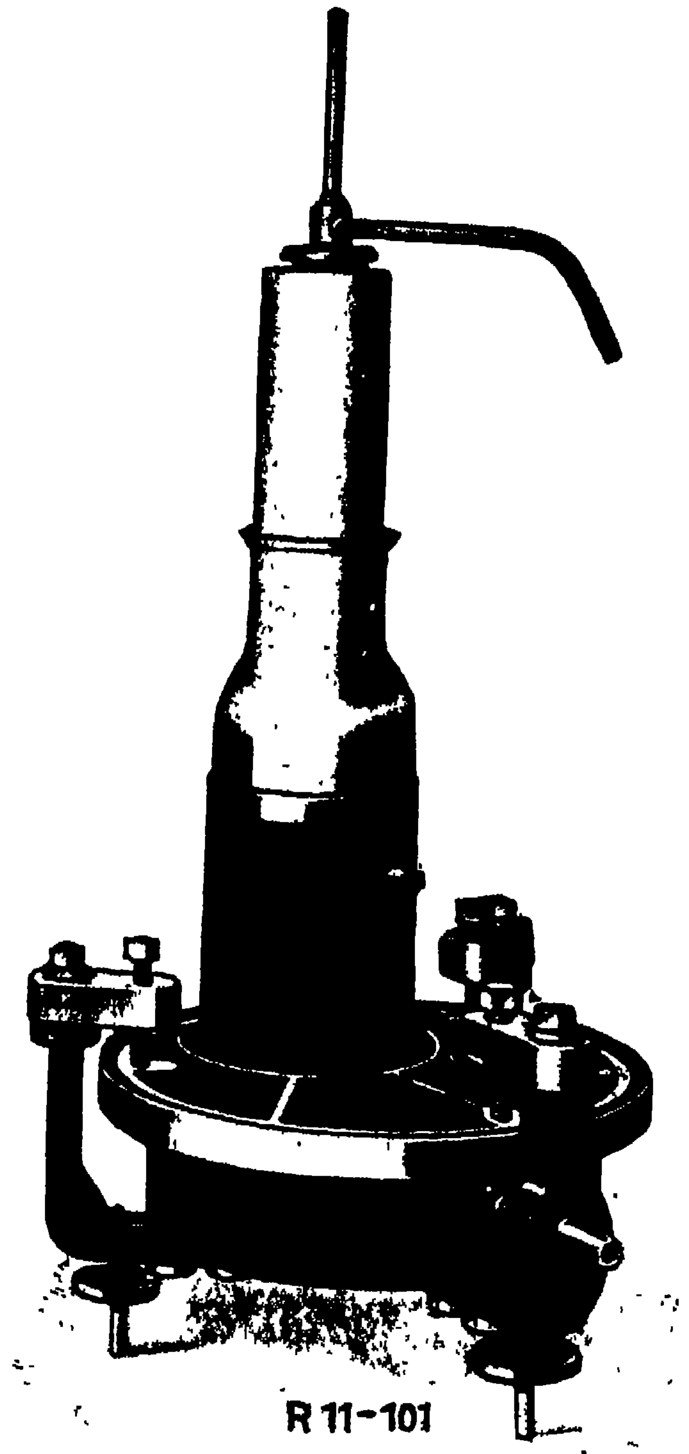



FIG. 143.—Combined Metal X-ray Tube and Vacuum Spectrograph (Siegbahn).

regular if gas is introduced, in order to neutralise the space charge, and Shearer's recent tubes are gas tubes. They are in permanent connection with an evacuating plant, and the rapidity with which the pressure is



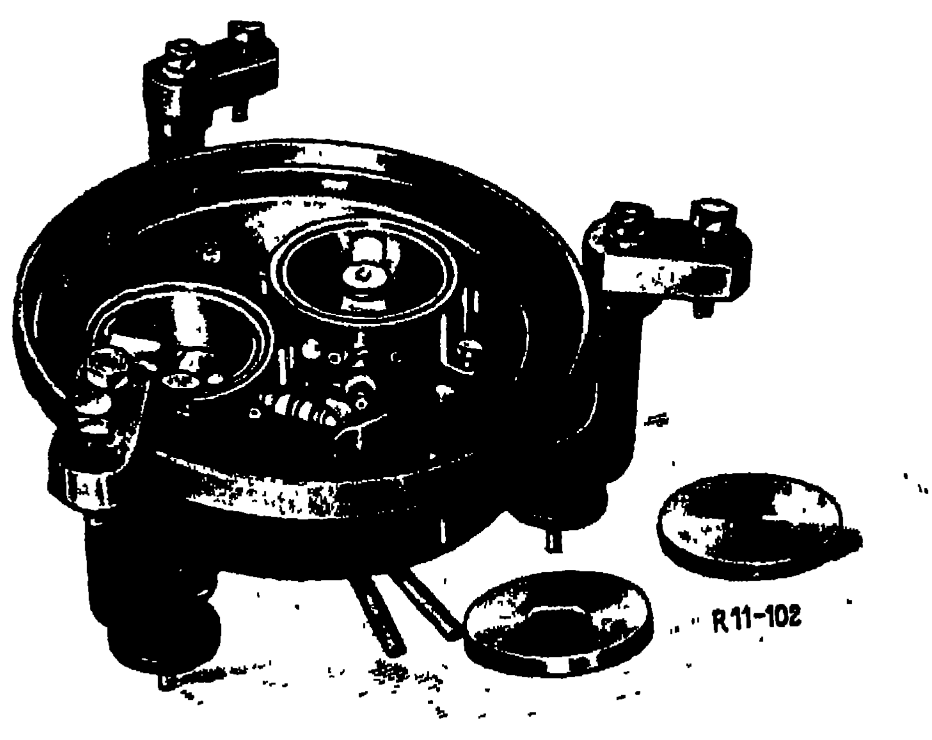




FIG. 144.—Schleede and Gantzchow Combined Metal Tube and Vacuum Spectrograph (Messrs. Koch and Sterzel).

[To face p. 175.

lowered to produce an X-ray vacuum has to be seen to be fully appreciated.

In the tube shown the hot cathode is insulated by a long glass sleeve with suitable arrangements to prevent movement. To prevent fracture of the glass-and-metal joint at the anode end metal, shields are used. The metallic anode end of the tube is water-cooled with separate water-cooling of the anode itself which emits radiation from thin aluminium windows,

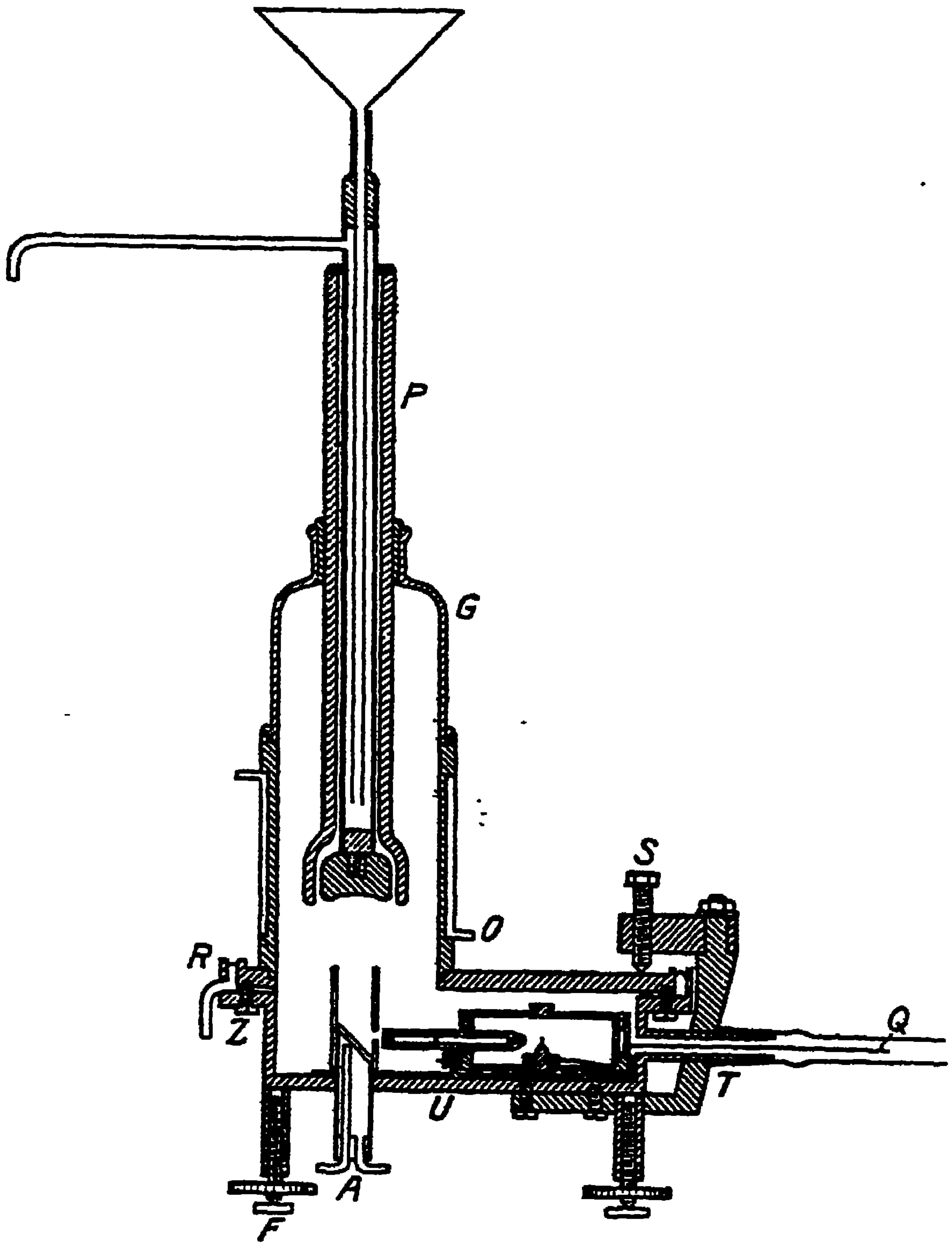



FIG. 145.—Metal X-ray Tube and Vacuum Spectrograph (Schleede and Gantzchow).

simply held in place by ordinary sealing wax. The voltage of operation is about 60 kv.

For research upon very soft X-radiation which is greatly absorbed by a few centimetres of air various metal tubes have been produced in conjunction with vacuum X-ray spectrographs, an example being shown in Fig. 143.

This is a hot filament tube insulated by a glass sleeve D, the electrons from which are incident upon a target M, the resulting X-radiation passing directly into the vacuum spectrograph V by G and S. All the metallic parts are water-cooled. The metallic body of the tube is maintained at earth potential and can therefore be safely touched.

Schleede and Gantzchow* have described such a metal tube and spectrograph combination shown in Fig. 144, and in section in Fig. 145.

The apparatus consists of an upper part O and lower part U, jointed above the centring screws F, the vacuum-proof connection being made by a rubber-mercury connection, which necessitates the upper and lower parts being pressed together by four pressure screws Z. The mercury for this seal can be supplied or withdrawn by the glass level in the rim R. The lower part is best machined from one piece of metal and is carried by four screws F. Within it is a water-cooled anticathode A and a tube T serves for connection to the vacuum

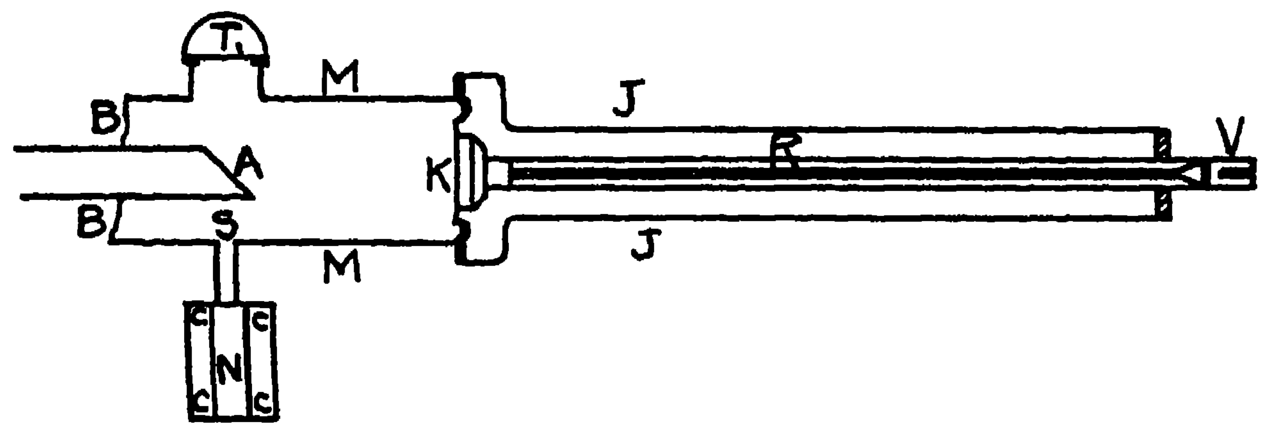



FIG. 146A.—Original Zehnder Metal Tube.

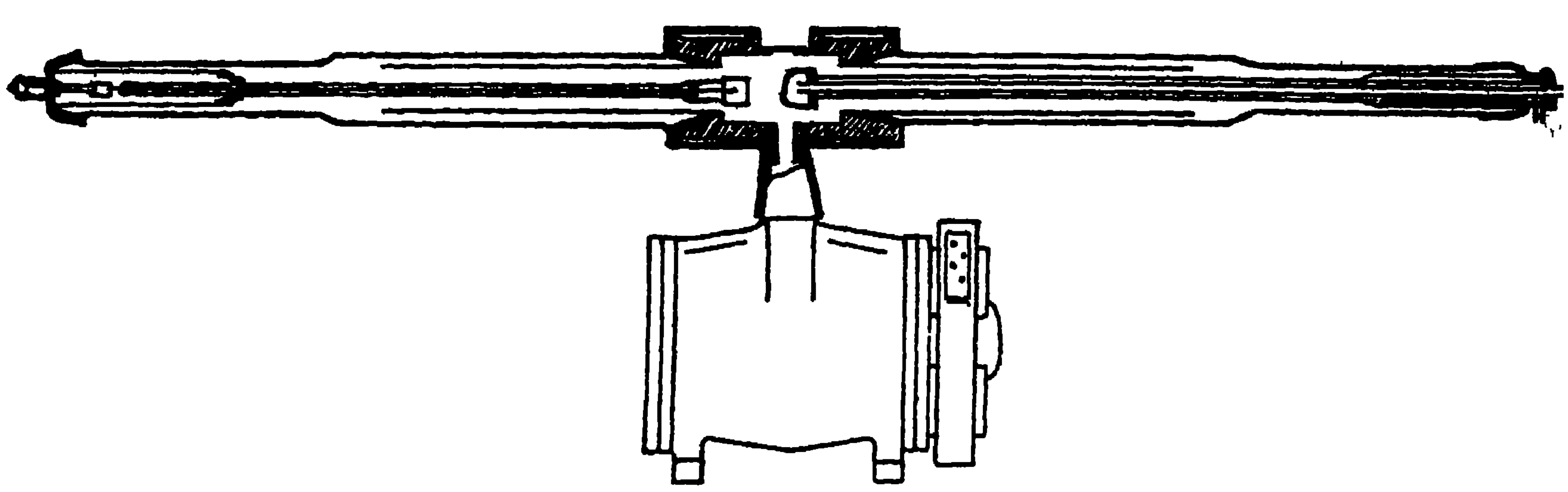


FIG. 146B.—Holweck Metal Tube of Zehnder Type.

pump. To diminish secondary electron action as far as possible, the anticathode is surrounded by an aluminium sleeve. The upper part can be air-cooled and carries an insulated cathode. This insulation is a difficulty when the tube is gas filled, as quartz and glass are unsuitable owing to their breakdown at high voltages. The best material is porcelain, as thick as possible. The porcelain tube P is inserted *viâ* a cemented conical fibre ring. The moderately heated cathode can be cooled by flowing water. Metallic parts are of brass. In the lower part the camera can be placed. This is also brass and the difficulty is to centre accurately the crystal container for spectrographic refraction. This crystal is rotated by clockwork. The vacuum is produced first by an oil molecular pump and then by a silica mercury vapour pump. In

* *Zeits. f. Phys.*, 15, p. 183, 1923.

the original paper details are given of a valve to regulate the vacuum and the dimensions of the apparatus.

Of the many other physical metal X-ray tubes that of Gerlach * and of Stintzing † warrant mention.

The first metal tube definitely intended for medical purposes is that of Zehnder. ‡ It is worthy of note that Zehnder, a physician to a hospital in Zurich, did not patent his design of metal tube, but expressed that he forebore to do so, as he hoped it would be generally used in the cause of humanity.

This tube (Fig. 146A) consists of a high-tension insulator J of porcelain to which is cemented a brass case M. Within this insulator is cemented a copper tube R, carrying a concave cathode K, this being actually embedded in the insulator, so that, with the exception of the concave surface, all the cathode is within the insulator and leakage is so prevented, emission of electrons only being possible from the concave surface.

The whole of the metal case M serves as anode and can, for protection purposes, be earthed. Within this chamber is the copper anticathode to which is soldered a target A of metal of high atomic weight, as tungsten.

Radiation passes from the target *viâ* a window T of glass or aluminium, cemented to the tube, or held in position by gutta-percha. The tube was designed to act as a gas tube and, to regulate the gas pressure, there is an accessory chamber CC. This contains a material, as carbon, that occludes gas and can be heated by inserting an electrical heater into N. In order to prevent this convenient type of heater from deviating the cathode stream, by reason of its magnetic field, it is wound non-inductively.

The anticathode is massive and intended for therapy, is water-cooled and can be altered in position to adjust the focus of the tube, or can be rotated to present a new surface when the target is pitted.

The insulator is 1 m. long and allows the highest therapeutic voltages to be used. Zehnder specifically mentions that the apparatus can be adapted to utilise a hot-filament cathode, by replacing the tube R by a double tube and introducing a filament in K which, being bowl-shaped, gives a sharply focussed cathode stream. In place of a single window T, two or more windows can be used, and these can be fitted with filters or a suitable diaphragm. Zehnder states the dimensions of the apparatus can be made as large as desired, so that very intense X-radiation outputs could be obtained for therapy. Also, as practical use showed great reduction of radiographic exposure times, the apparatus is suggested as useful for very rapid cinematographic X-ray work.

* *Verh. d. deut. Phys. Ges.*, 2, p. 55, 1921.
† *Zeits. f. Phys. Chem.*, 107, p. 168, 1923.
‡ *Elek. tech. Zeits.*, p. 49, 1915. *Ann. der Phys.*, 46, p. 824, 1915.

Amongst other advantages Zehnder points out that with such tubes many X-ray beams could, by means of crystal grids, be simultaneously focussed upon a neoplastic growth, and there is no limit, as with glass X-ray tubes, to the shortness of wavelength which could be produced, so that X-radiation approaching the $\gamma$-radiation of radium could be produced at high voltages. The advantages of self-cooling, earthing for protection, etc., were fully recognised by Zehnder.

Holweck * has recently used a metallic tube of the Zehnder type (Fig. 147B), capable of working at 200 kv. and passing about 12 milliamperes. Both the anticathode and the metallic body were water-cooled, and filtered radiation was emitted *viâ* a copper, or zinc, window. The tube was in permanent connection with Holweck's molecular pump (Fig. 13).

The Zehnder tube is anterior in date to those tubes already mentioned, with the exception of those of Davis and of Lindemann, although Siegbahn produced a physical metal tube in 1915.

The Zehnder tube again drew attention to the possibilities of metal tubes and, in 1917, Coolidge published † a description of a metallic Coolidge tube, fuller details of which are given in Brit. Patent 108,793/1916. It differs in detail from the Zehnder tube in actually utilising a filamentary cathode as proposed by Zehnder and in the provision of metallic shields, to protect the glass-and-metal joints from the electronic bombardment. Also the radiation is emitted *viâ* a metallic window perpendicularly to the tube axis, with advantages already dealt with (p. 108).

Alternative forms of this tube are shown in Figs. 147A and 147B. The envelope 1 is of copper and contains an insulating enclosure 2 of glass. In order to join the copper and glass sections a platinum portion 3 is introduced. Within this glass container 3, is a glass tube 6, which serves to protect the glass-and-metal joint of 2 and 3 from electronic bombardment and fracture. The first electrons given off from the filament 7 charge the tube 6 negatively, so that few or no electrons reach the junction 5, and fracture is so prevented.

The current to the filament is conducted by leads 10 and 11 throughout the length of the glass portion of the tube by the method shown, the filament being surrounded by a focussing device 8. The target 15 is cooled by water *viâ* inlet 16 and outlet 17. Radiation is only emitted *viâ* the window 19, which is of glass or aluminium.

An alternative form (Fig. 147B) of the tube has the whole of the metal part within a cooling tank, the anticathode being the end of the container 20, from which rays pass *viâ* the water out of a window 22. The difficulty common to all metal tubes in general is that they oxidise during manufacture and when, in operation, the tube becomes heated, the oxides

* *Bull. Soc. Rad.*, December, 1923. *Jour. de Phys.*, 3, p. 64, 1922. *Rev. d'Optique*, 1, p. 274, 1922.

† *Amer. Jour. of Rönt.*, 1917.

are broken down and gas is evolved, so destroying the vacuum. To overcome this Coolidge treats the heated tube with hydrogen, which reduces the oxide, and the resulting water vapour is pumped off before sealing. The filament and target are tungsten, as in the glass Coolidge tube.

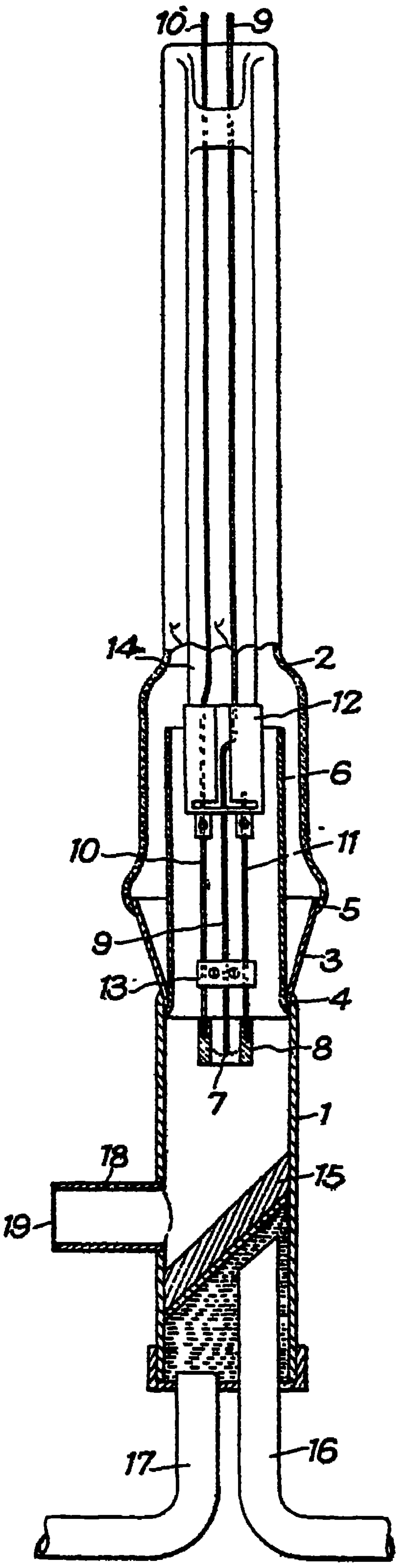



FIG. 147A.

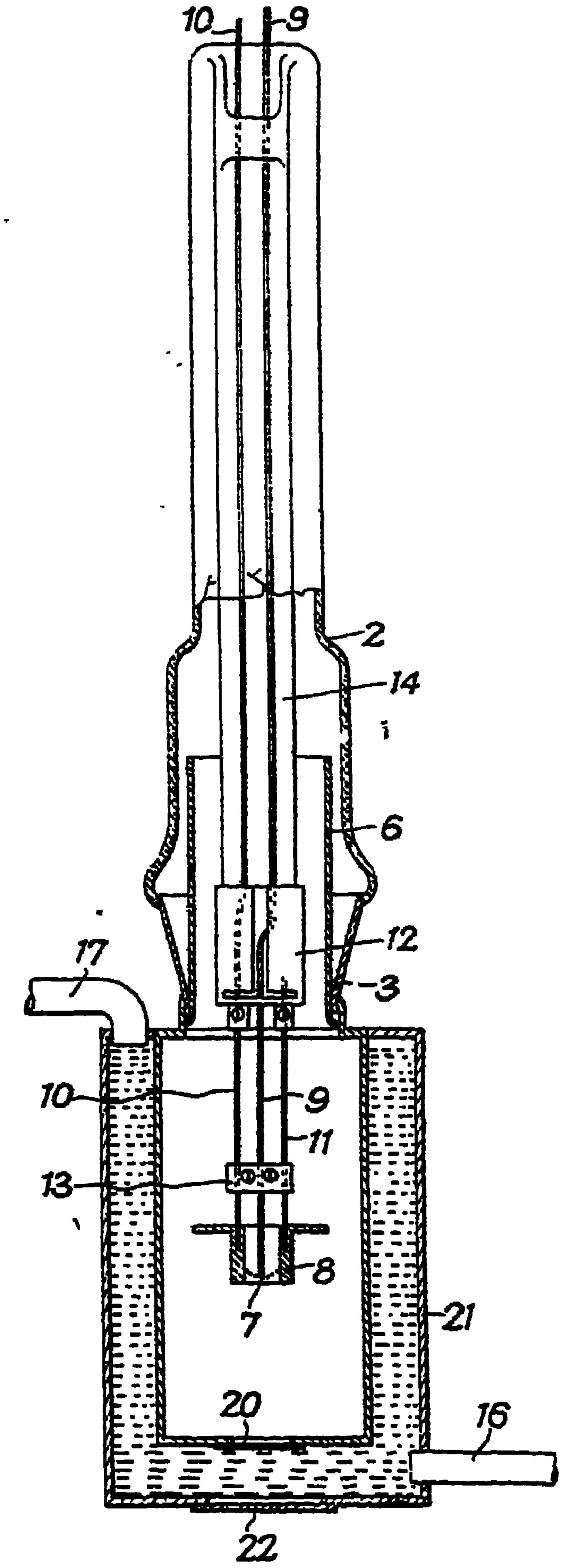



FIG. 147B.

Metal Tubes (Coolidge).

It is of interest that Coolidge in detailing the advantages of a metal tube, suggests that it can be made of small dimensions for actual insertion into a body cavity, without danger to a patient if the metallic container is earthed.

Whilst Coolidge apparently intended this tube for medical purposes, the author has been unable to trace any description of actual medical use.

Holweck (Brit. Patent 189,137/1921) has described a tube combining the advantages of a metal tube, with the advantage that its metallic case is directly connected with that of the exciting transformer, so that it can be directly earthed, and there are no external dangerous and corona-producing high-tension leads.

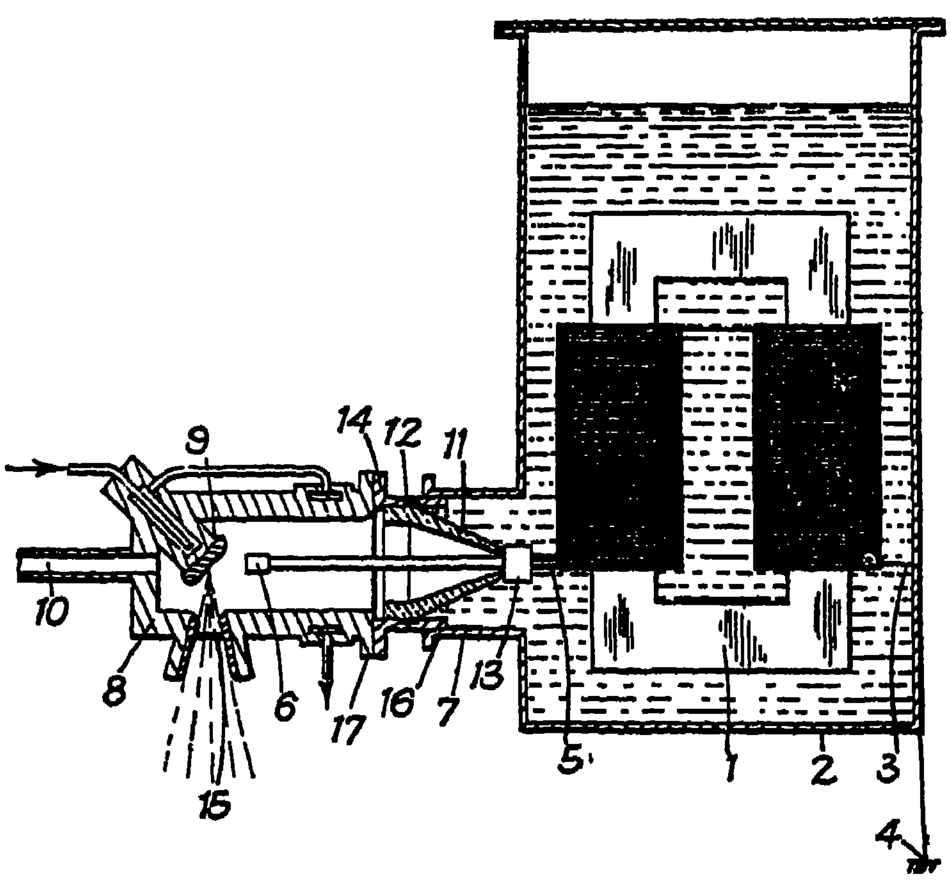



FIG. 148.—Holweck's Metal Tube.

Coolidge had previously obtained the same advantages by placing a glass X-ray tube within the transformer tank itself, but in this case the tube is not easily accessible and, in case of tube puncture, considerable danger arises due to the presence of the possibly white-hot anode within the oil tank. Holweck's device overcomes this defect. The construction of the tube is evident from Fig. 148, the especial features being that the X-ray tube is, at its cathode end, in actual contact with the oil of the transformer, and that the tube may, by means of a suitable joint 16, be rotated about the horizontal axis to give a variation in the direction of emission of radiation *viâ* the glass, or aluminium, window 15.

The tube body is water-cooled, the water circulating around the anode, and the tube may be in permanent connection with the evacuating pump. To renew the filament the tube may be opened at the joint 14.

## PHILIPS METAL TUBE

The first metal tube to be used for medical rather than physical purposes appears to be that of Zehnder. The Coolidge metal tube described appears to have never been used in actual medical practice, as distinct from laboratory use.

To bring an entirely new tube into extended medical use requires an extensive propaganda organisation which has only in recent years been provided by the lamp concern, Messrs. Philips of Holland, although such a medical metal X-ray tube was patented by the Viefa-Werke * in 1915 and by L. Wolfram† in 1917.

* German Patent 300,991/1915.
† German Patent 310,368/1917.

This tube, largely due to Bouwers and Holst of this company, has been well used upon the Continent and is being more and more used in England. It appears to offer undoubted practical advantages. Its price is similar to that of other electron tubes.

Metal tubes have now been satisfactorily produced to operate at deep therapy voltages of 220 kv., and various smaller voltage tubes for treatment and diagnosis exist. The design of these tubes are covered by various patents * and they are distinguished by many novel features, in addition to the use of a metallic envelope, which are as follows ;—

(1) The use of a gas filling.

(2) The use of a filament.

(3) The use of a flat tungsten target to prevent gas ionisation.

(4) The close approximation of the filamentary cathode to the target, to prevent gas ionisation.

(5) Special methods of distributing the applied potential to avoid ionisation and rupture at the metal-and-glass joints (Fig. 48).

(6) The use of an indented target (Fig. 78A).

(7) The emission of radiation normal to the target.

(8) The use of chrome-iron to facilitate even thermal expansion and non-fracture at the metal-and-glass joints.

The most novel feature is the method of avoiding ionisation when the tube is gas filled, so evading any conflict with the Coolidge patents with respect to vacua.

Many investigators and in particular Richardson have studied the conditions for the ionisation of gases. It is well known that of the common gases hydrogen and helium are more difficult to ionise (see p. 75). We have also seen that to facilitate the auto-electronic discharge it is necessary to have point electrodes. Conversely to prevent such a discharge we must use flat electrodes. Again, if we have at our disposal a source of electrons, such as a filament surrounded by gas, an electron is unable to ionise the gas until it attains a certain definite speed, actually determined by the work necessary to remove an electron from the outer orbits of the gas atom.

If an electron is emitted at a low velocity within an electrostatic field it must necessarily pass over a path of a definite length before it can accelerate and acquire the kinetic energy necessary for critical ionisation and afterwards undergo the chance of an ionising collision. If it is arranged for it to encounter a target electrode before it is likely to undergo such an ionising encounter then all its energy is given to the target to produce X and other radiation. Ionisation of the intervening gas under such conditions will not appreciably occur. If we recollect that the free mean path of a molecule may range up to 10 cm. and

* Brit. Patents 208,108/1922, 228,592/1923, 228,130/1924, 232,202/1924, 235,141/1924, 235,892/1924, 237,580/1924, 243,310/1924.

above at comparatively high gas pressures, we see we shall have little risk of ionisation if we place the filament and target electrodes at 5 cm. distance, and, in practice, in the Philips tube the distance is much less.

The action of the accessory gas tube anode has been explained upon this consideration of this electrode increasing the electronic path and so causing ionisation (p. 97). We have also seen that close approximation of flat plate electrodes tends to diminish ionisation and gas discharge, this fact being utilised in the well-known quenched spark gap (Vol. I.).

There is therefore no fundamental reason why with a suitable gas difficult to ionise, as hydrogen or helium, combined with close approximation of the electrodes, it should not be possible to produce a purely electronic discharge in spite of the presence of gas.* On the contrary, Philips claim that such a gas serves a useful purpose in that, by the molecular collisions with the target, it removes undesired heat energy from the target. Such heat would tend to make the target itself a source of electrons and so to give the tube non-rectifying properties as well as the heat assisting to cause ionisation of the intervening gas.

In an early patent of the Philips tube (Brit. Patent 203,784/1922) the patentees specify the use of a degree of vacuum above ·00006 mm. of mercury, *i.e.*, above the pressure specified by the Coolidge patents and below the pressure of ·001 mm. of mercury, as in gas tubes. It is however stated that it is possible to obtain a non-ionised discharge with gas pressures as high as 1 mm. of mercury, if conditions such as approximation of the electrodes are suitable.

Regarded from the aspect of electrostatic flux the use of a flat electrode serves to distribute the electrostatic flux, so that the maximum value at which breakdown and ionisation occurs is not reached.

In Brit. Patent 208,108/1922 the use of a re-entrant anode is specified, and apparently, in order to avoid a space-charge effect, the metallic portion of the tube is given a more negative potential than the insulated filament by use of a filament resistance 32, as shown in Fig. 136. The metal, having a greater negative potential than the filament, then tends to repel the electrons emitted to the field between filament and anode where they are drawn to the anode. The use of a re-entrant anode gives a larger insulating glass area and length over which the anode potential is distributed, and so allows a reduction of the overall length of the tube.

In the majority of these metal tubes the filament is placed near to and opposite the flat target, a distance of ·8 cm. for 100 kv. being mentioned in one case, and, as is well known, the emission of the radiation normal

* The physical aspects are discussed by: Holst and Oosterhuis, *Phil. Mag.*, 46, p. 1117, 1923; *Comptes Rendus*, 175, p. 577, 1922; and Taylor, *Phil. Mag.*, 3, p. 753, 1927.

to the target gives greater average penetration of the radiation. The presence of the thin filament through which the radiation can pass, gives no disturbing effect by casting a shadow, particularly as any interception of radiation by the filament is, at a relatively distant point, obscured by the effect of penumbra.

The flat target is protected against electronic impact, except at its centre, by a diaphragm of metal of low X-radiation emission and so overcomes ionisation which might occur, due to irregularities of the electrostatic field at the target periphery.

The use of a flat target also allows the use of an indented hemispherical anode (Brit. Patent 237,580/1924). This indentation has no effect as regards scattering of the radiation (as occurs with an irregularly pitted inclined target), as is shown in Fig. 78B. The use of such an indentation gives a greater area of metal over which the electron bombardment and heat production is distributed, whilst at the same time no loss of focus can result. It is stated that a hemisphere of 2·5 mm. base and depth 4·5 mm. gives a fourfold area to that of a plane non-indented target. The distribution of such heat, which would assist gas ionisation, is of particular importance in this gas-filled electron tube.

In the original patent (Brit. Patent 208,108/1922) no remark is made regarding the pressure and nature of the gas except that it is above the Coolidge limit of ·00006 mm. of mercury. In a later patent (Brit. Patent 228,592/1923) the gas is stated to be hydrogen or helium, and pressures up to 1 mm. of mercury can be used, without ionisation occurring. One cause of gas ionisation is stated to be due to secondary electrons, released from the target itself, by primary electronic bombardment. If the filament is closely situated to the anode and if the potential difference is sufficiently great, the potential field between the electrodes is so intense that secondary electrons are unable to pass against the direction of this strong field. They therefore return to the target before they have traversed a path of sufficient length to ensure an encounter and ionisation result with a molecule of the gas. By placing the filament close to the target and making the latter very flat it is ensured that electrons from the filament only strike the centre of the target, where over-concentration of electrostatic flux cannot occur, and where the electrons are restricted to a short direct path, so minimising the chance of encounter with a gas molecule. It is stated that with a distance of cathode and anode of only ·8 cm. a tube can be satisfactorily operated at 100 kv., with gas pressures varying between ·01 to 1 mm. of mercury. Whilst the gas aids cooling of the anode one would expect that the approximation of the anode to the filament would result in the temperature of the latter and its electronic emission being varied by direct heat radiation from the anode, but this is stated not to occur.*

* A gas filling for an electron tube has since been used by Müller (Brit. Patent

The active target area, as allowed by the intervening screen, is mentioned as of 20 mm. diameter, which gives a focal spot of only 2 mm. diameter. Of the actual gas pressure used no definite statement is made, but it appears to be between ·01 to ·03 mm. of mercury, *i.e.*, much above that of the normal gas tube. Gas ionisation not occurring, the discharge partakes of a purely electronic nature and consequently retains the

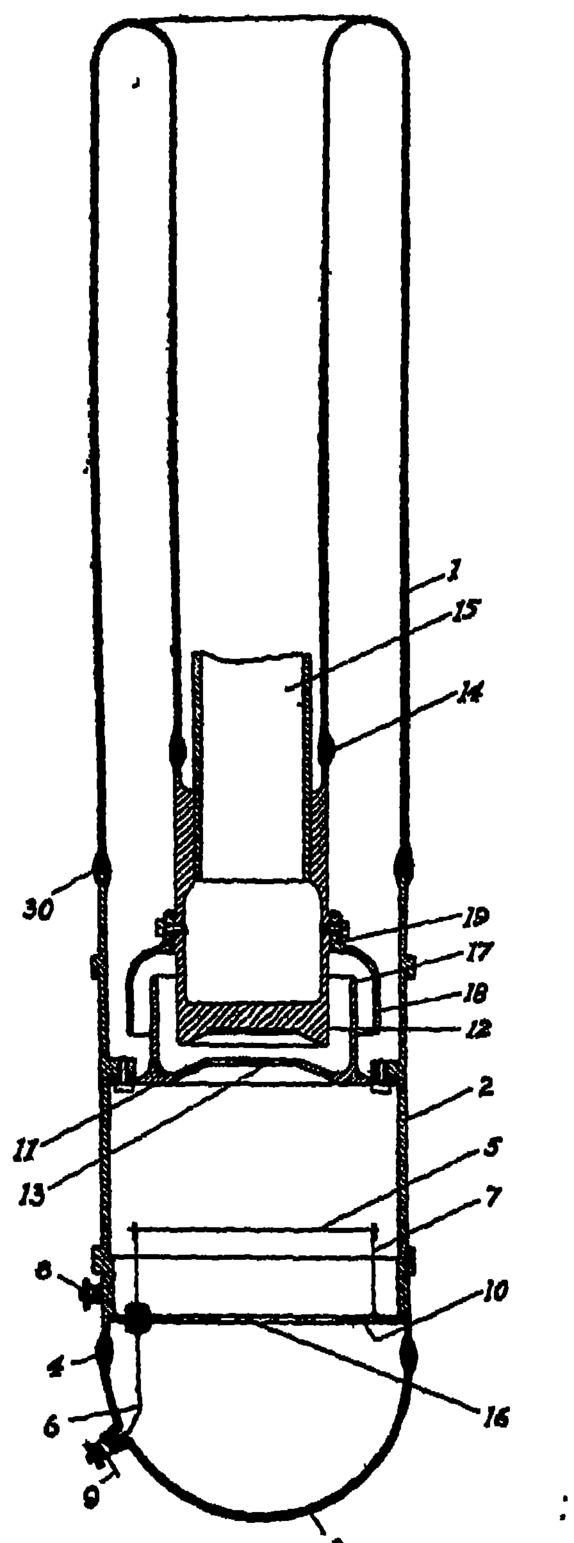



FIG. 149.—Messrs. Philips' Labyrinth Shield.

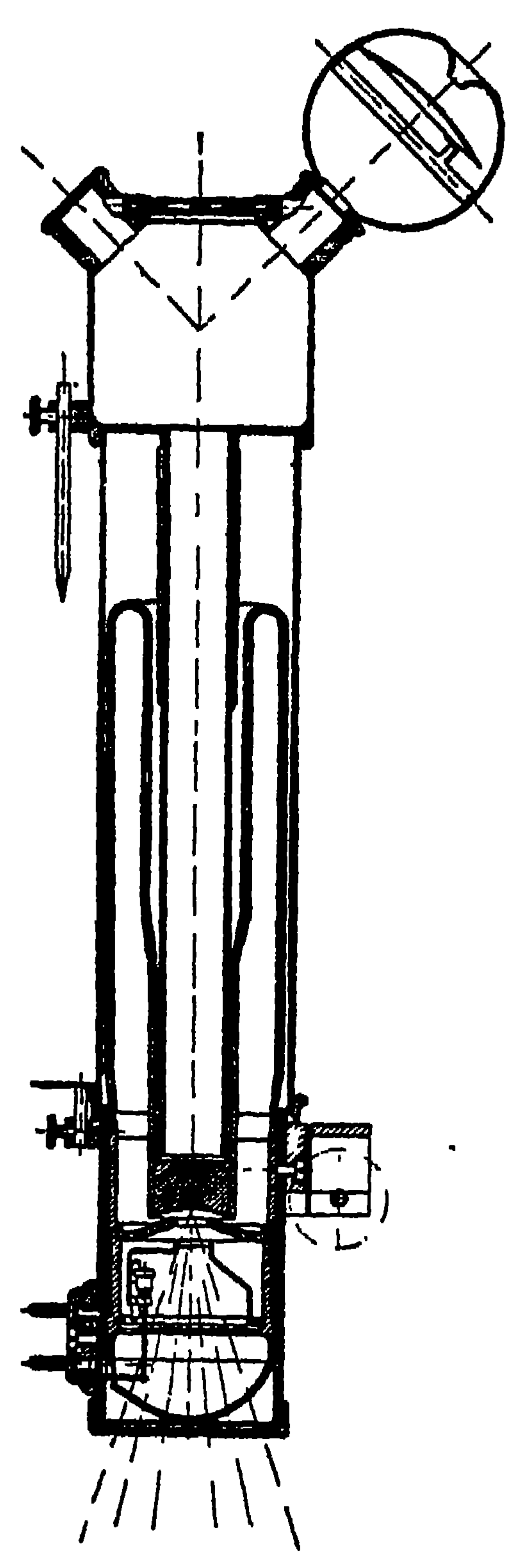


FIG. 150B.—Metallic Tube for Low Voltages.

advantages of such a discharge with separate regulation of intensity (current) and quality (voltage).

As already mentioned, the difficulty with all metallic tubes, or, more correctly, composite metal and glass tubes, is at the metal-and-glass

258,589/1926) and Dessauer (Brit. Patent 262,906/1925). Dessauer appears to prevent gaseous ionisation by withdrawal of the filamentary cathode within the cathode stem, so that electrons can only pass to the target and not to the bulb walls. This would appear to confirm the view of Dauvillier that electron production in the gas tube is due to bombardment of the bulb itself and not to ionisation of gas between cathode and anode, as usually stated (see p. 67).


FIG. 150A.—" Metallix " Tube for Low Voltages.

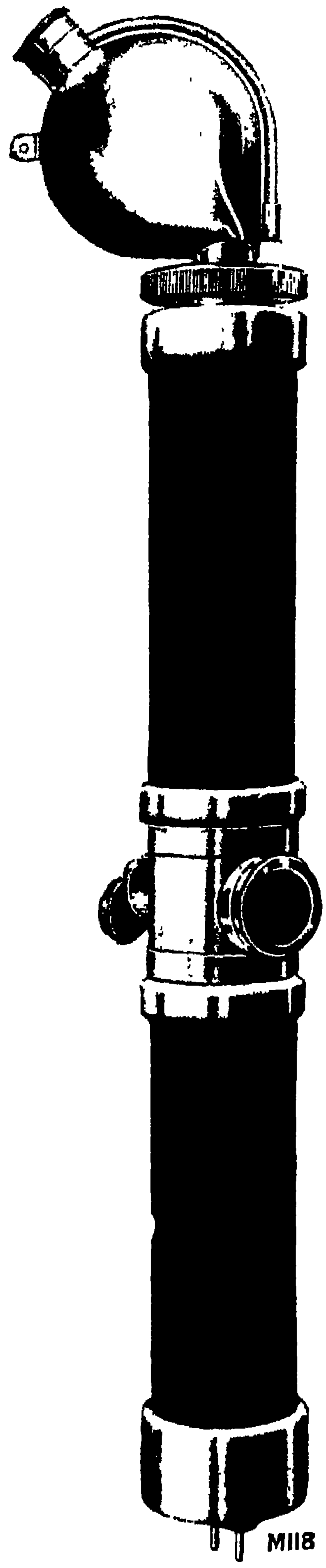



FIG. 151A.—" Metallix " Tube for High Voltages.

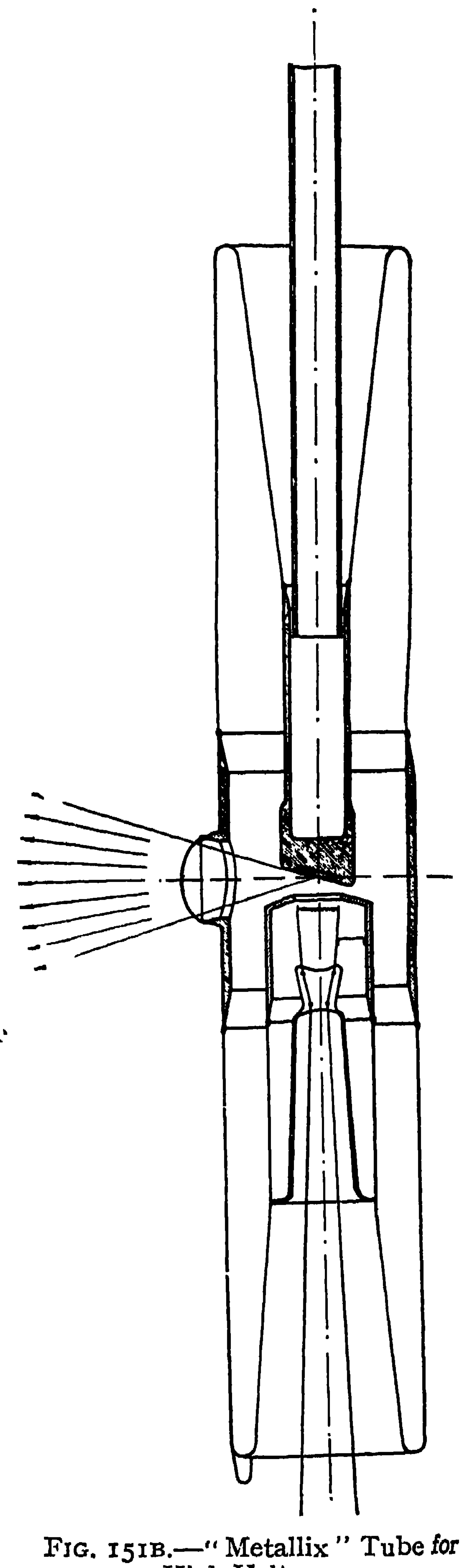


FIG. 151B.—" Metallix " Tube for High Voltages.

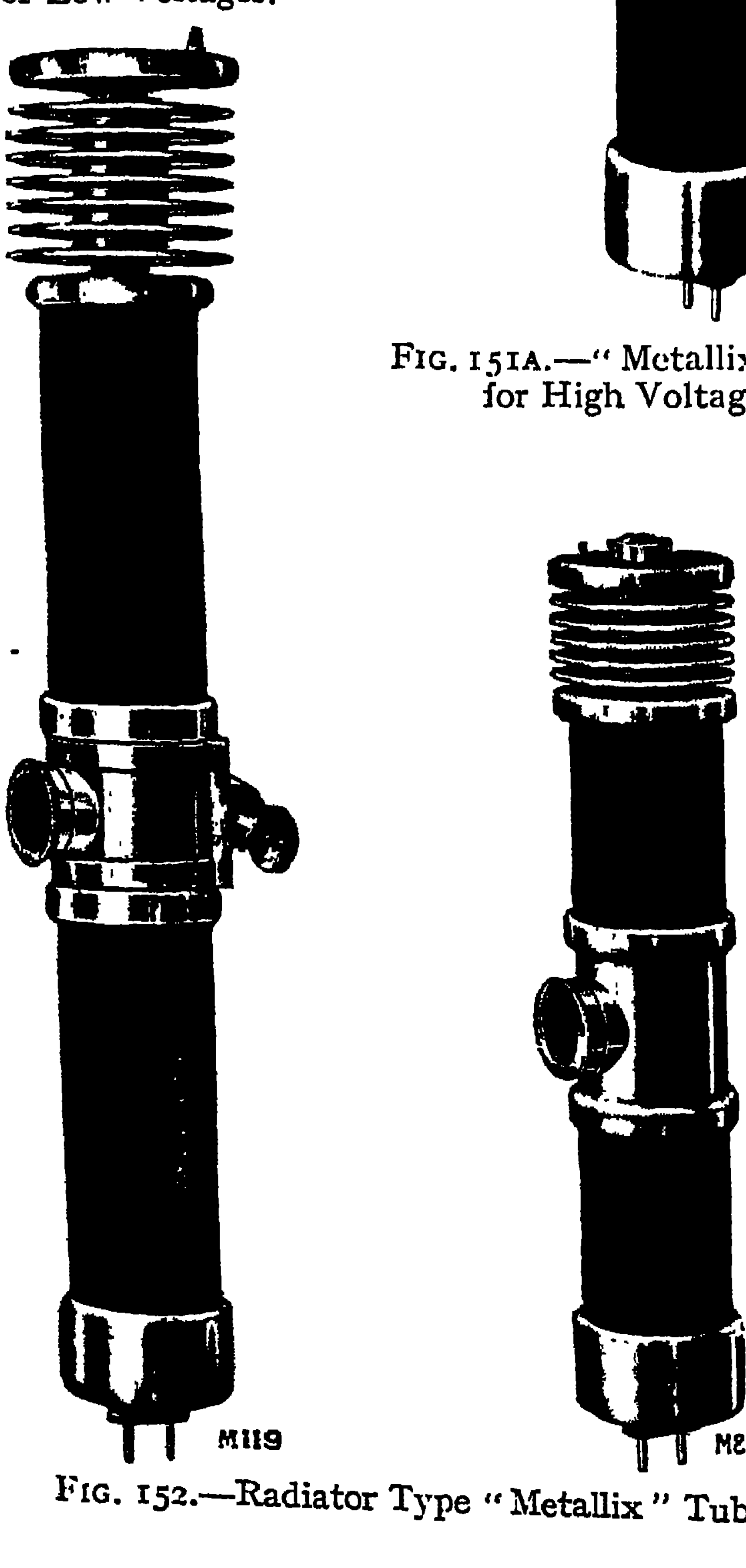



FIG. 152.—Radiator Type " Metallix " Tubes.

joints. This is due to the abrupt variation of the dielectric properties causing an abrupt variation of electrostatic field across the joint, so that any gas ion or electron which may be present is caused to obtain great velocity in this region and, by impact upon the wall, gives rise to further ionisation. Such bombardment causes the region of junction to be heated and, owing to uneven expansion, fracture results.

Philips use for this joint chrome iron having the same expansion as the glass, to ensure equality of expansion in the joint.

They further protect the joint by a metallic shield, which carries the region of abrupt dielectric stress to the edge of the shield and away from the potentially weak glass-and-metal junction.

Instead of a plane metal shield they use (Brit. Patent 232,202/1924) labyrinth shield as shown in Fig. 149. In this type of shield it is impossible for an electron to pass directly from the region of the high potential anode 12 to the joint 30, without its direction of motion being several times reversed during passage by shields 17 and 18, which is unlikely, if not impossible.

Further, these shields, which may arise both from the anode and the cathode, are, by suitable leads, kept at potentials of decreasing order from the anode outwards, so preventing any localised region of concentration of potential fall. The shields are also connected to electrodes in the glass wall itself, serving to distribute the potential across the glass insulation, if these are connected to various steps of the high-tension transformer, as evident from Fig. 48.

The Philips tubes are manufactured in various types differing in form and focus for particular purposes, for example, dental radiography, general radiography, superficial therapy up to a 6-in. spark gap, general radiography, general therapy, and deep therapy at 200 kv., the latter, in view of the re-entrant glass sleeve, having an overall length of 55 cm. as against 80 cm., or more in the more common electron tubes.

The smaller voltage tubes are of torchlike form (Figs. 150A and 150B), and, as the metal end nearest the patient can be used at earth potential, the tube can, except for the anode connection, be touched during operation. The protection of the metallic sheath is equivalent to about 2·3 mm. of lead. The provision of a safety spark gap to prevent overloading is seen in Fig. 150B.

In the deep therapy tubes the cathode is not earthed, but a metallic central portion between the high-tension ends is earthed and may be touched with safety during operation, or directly connected to an earthed tube holder of simple form. In these tubes the anode is no longer normal to the electron beam, but inclined at an angle of 30 degrees to the beam and not at 45 degrees, as in the ordinary gas and electron tubes. The re-entrant walls should be noted in the sectional drawing

of Fig. 151B. Such tubes are not, as in the lower voltages tubes, fitted with a glass radiation window, but with a chrome-iron window of ·3 mm. thickness, so that the emitted radiation is filtered from the softer components. The protection of the tube is in these cases equivalent to 5 or 6 mm. of lead and is sufficient to prevent all undesired stray radiation.

Until recently these tubes have been water-cooled, with the efficient cooling of this method, but with its practical disadvantages. Tubes are however now produced (Fig. 152) fitted with the more convenient, but less efficient, radiator cooling.

According to requirements, some of these metallic tubes are self-rectifying and can be directly inserted in an alternating current circuit, but the tubes for the higher voltages require rectified current.

These tubes have not yet been so extensively used in England to allow a comparison with other types of tube. Most reports appear to be in their favour as regards practical operation and there can be no question that their use, with the consequent advantages of economy of accessory protective appliances (which has prejudiced the tube in the eyes of some of the apparatus manufacturers) is extending. The writer has found them very advantageous for standardised routine radiography. (For recent improvements of the " Metallix " tube see Appendix II.)

## ACCESSORY ELECTRODES

The anode usually present in the gas tube may be considered as an accessory electrode, but its extensive use has warranted its separate treatment. Similarly the Lilienfeld tube is a tube with accessory electrodes.

At various periods during the history of X-radiology additional electrodes have been introduced into the X-ray tube for specific purposes. It is remarkable that the first British patent for X-ray apparatus, due to E. Böhm (Brit. Patent 22,794/1896), a year after Röntgen's discovery, was a tube with an accessory electrode, and in this respect is practically identical with a similar tube recently described by Tozer * and shown in Fig. 153.

Similar ring electrode tubes were used by L. Wright † prior to 1897.

For the purpose of generating X-radiation by means of high-frequency oscillatory currents, Lilienfeld (Brit. Patent 145,084/1918) and Loewe (Brit. Patent 149,013/1914) have used four-electrode tubes, but their con-

* *Brit. Jour. Rad.*, 22, p. 80, April, 1926.
† "The Induction Coil in Practical Work," L. Wright, 1897.

sideration is deferred until this method of X-ray tube excitation is discussed (Chapter VII.).

It may however be mentioned here that the introduction of a third electrode into an X-ray tube constitutes a triode valve, such as used in practice to generate high-frequency oscillations. For this reason there can be little doubt such three-electrode X-ray tubes are more prone to generate undesired high-frequency oscillations, dangerous to high inductive windings, than two-electrode tubes.

The accessory electrode of the tube of Böhm and of Tozer is stated by Tozer to have the purposes of ;—

(1) Controlling the penetration of the gas tube, independently of current, as in the electron tube, by varying the electron velocity and resulting quality of X-radiation.

(2) Varying the focus.

Whilst the action of this accessory ring electrode appears to have

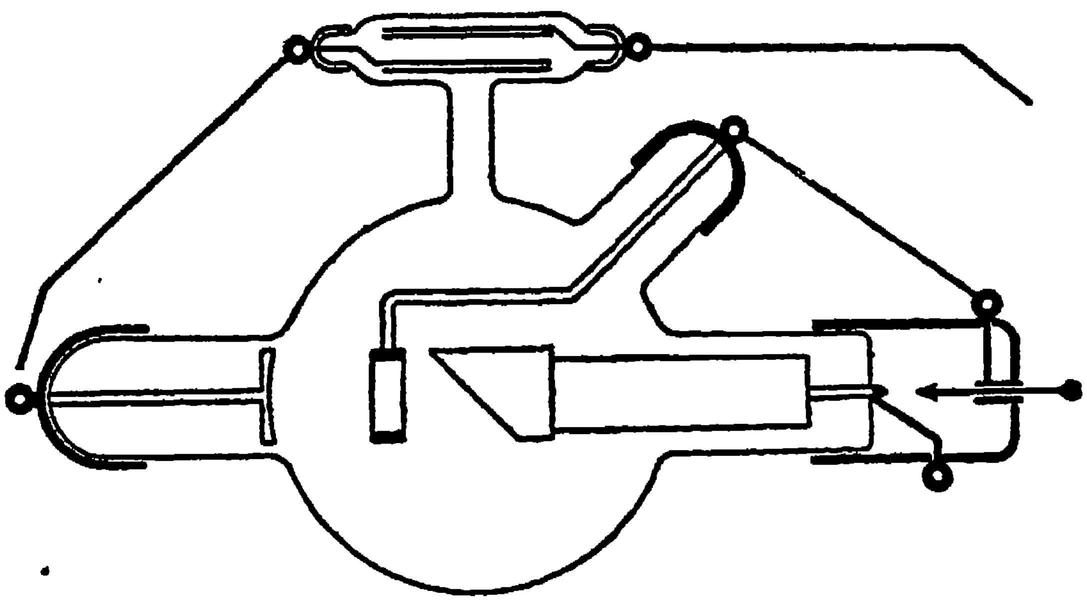


FIG. 153.—Tozer Tube.

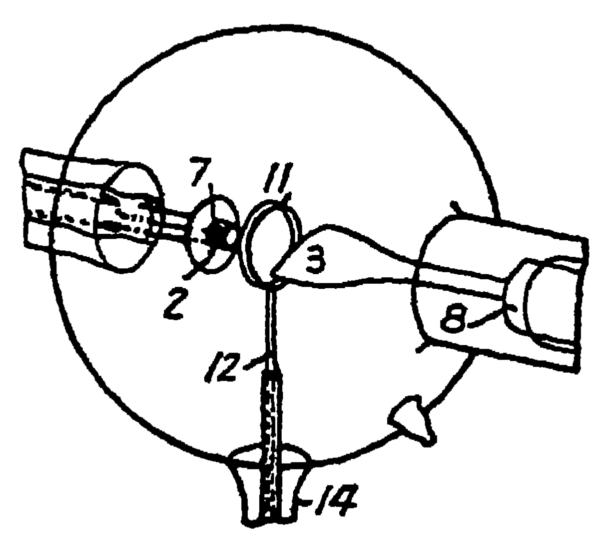



FIG. 154.

been considered intricate in the discussion following Tozer's demonstration, it would appear to be fundamentally simple.

If the accessory ring electrode is given a negative charge it will tend to repulse electrons emitted from the cathode which must pass through it.

Additional work must then be expended to force the electrons through the ring owing to the electrons of the electron beam being more closely approximated before entering the ring. After passage *viâ* the ring and when the electrons can extend over a wider area, the energy which has been stored during the electronic compression, is released and causes increased electronic velocity. The result is that the electrons encounter the tube target at greater speeds than would be the case were this electrode absent and, by the Einstein-Planck relationship, the quality of radiation must be improved.

A mechanical analogy to the process would be the forced passage of a gas *viâ* a small orifice from a large reservoir. As a result the gas molecules store up energy by their closer approximation in the orifice and,

as soon as their pressure is released after passage *viâ* the orifice, they move with greater velocity, so giving an increased pressure.

Such a third electrode allows the quality of the radiation emitted by the tube to be varied, as regards its quality, according to the charge upon the accessory electrode, and largely independent of tube current, so partaking of the character of the electron tube discharge. It follows that if the ring were given a positive charge instead of a negative charge the ring would tend to cause the electron beam to spread and, by causing this beam to have a greater cross-sectional area, reduce the energy necessary for the passage of the electrons and so to render the tube soft. The ring will modify the focus of the electron beam upon the target, subject to the relative positions of cathode, ring and target.

After passage *viâ* the ring with a negative charge the electron beam

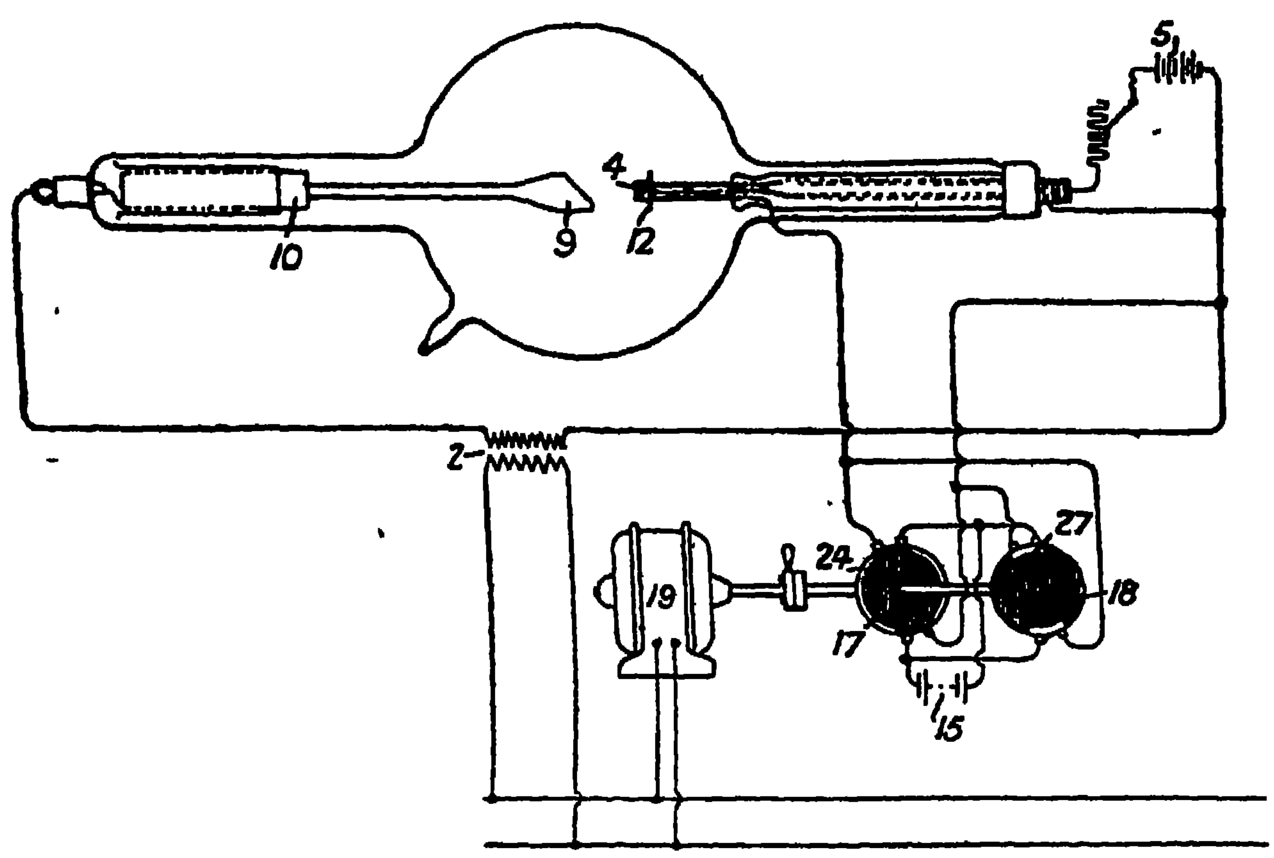



FIG. 155.

is constricted, and its area upon a closely situated target is a circle of small dimensions, *i.e.*, the tube is sharply focussed. This focus will be dependent upon the relative negative charge of the ring electrode. A positive charge will broaden the focus.

Tozer gives the ring a negative potential by connecting the ring *viâ* a spark gap to the anticathode. In this respect the method is identical to a method of varying hardness due to Dessauer (Brit. Patent 7,858/1902), who varied the spark-gap distance between the anticathode and an accessory electrode. The only distinction in the method of Dessauer is that his accessory electrode was of flat form and would act to give a parabolic electron trajectory between cathode and target. To force electrons over this longer path necessitated greater energy, recovered on impact at the target, and the tube hardness was thereby increased.

A practically identical method to that of Tozer for the gas tube, is that of the B.T.H. Company for the electron tube (Brit. Patent 9,346/1915),

who utilised such a ring electrode 11 (Fig. 154) to give a variation of tube focus, but the use of the tube must equally have caused a variation of hardness.

A more novel method is due to the same company (Brit. Patent 9,690/1915), who surround the filamentary cathode by an iron or molybdenum focussing ring 12 (Fig. 155).

The potential given to this ring, with respect to the filamentary cathode, is varied, by means of commutating discs 17 and 18, synchronous with the high-tension discharge. If this commutator is arranged to give the accessory anode a negative charge it will repel electrons and prevent their emission from the cathode, and so tend to hinder passage of current *viâ* the tube. If given a positive charge, it will assist the emission of electrons and, by aiding the passage of current *viâ* the tube, will render the tube soft.

As in the ordinary triode valve, the charge of the accessory (or grid) electrode will control the energy passing *viâ* the tube. Such a method, by appropriate selection of segments of the commutator, allows the energy *viâ* the tube to be suppressed, or assisted, at any part of the alternating half-cycle of the synchronous voltage actuating the main discharge.

Hence undesired soft radiation, corresponding to the lower voltage values of the sine form energy at the beginning and end of each half-cycle, can be suppressed, and the discharge at the peak of the half-cycle aided.

A fundamentally similar arrangement is protected by Philips (Brit. Patent 182,750/1927), with the addition that the grid electrode commutator is directly mounted upon the high-tension synchronous rectifier and, it is stated, the potential of the third electrode can be so arranged that it opposes the flow of current *viâ* the tube at the moment of circuit interruption by the high-tension commutator and so prevents sparking of the commutator at this moment.

In Brit. Patent 151,999/1913, the B.T.H. Company and Langmuir adopted a similar arrangement in order to vary the size of the focal spot of a cathode filament upon the anode. The cathode is surrounded by a sleeve maintained at an appropriate direct or alternating potential with respect to the cathode, such potential determining the size of the focal spot.

Müller has adopted a third electrode in his " Media " tube (Fig. 156). In this a wide mesh grid G, supported by an aluminium sleeve, surrounds the filament F specially constructed to give greater electron outputs than the similar Coolidge tube filament.

Connection is made between the grid and the filament *viâ* a high resistance R, of about a dozen megohms, in order to give the grid a strongly negative charge. This charge in consequence repels the electrons coming from the cathode, under the voltages of the lower portions of the

alternating voltage half-cycles, whilst, it is stated, increasing the highest voltage peaks since the filament can be heated to a greater extent than is the case in the normal Coolidge tube, where the filament is not protected by such a grid electrode. By suppressing the lower values of the alternating voltage unnecessary heating of the target is avoided.

Müller (Brit. Patent 247,568/1925) has also produced a further three-electrode electronic tube, where the accessory electrode has the very important function of causing the focus to vary automatically, according to the energy passing *viâ* the tube, and this tube is termed the "Autofok" tube.

In radiological practice it is necessary to have an X-ray tube which, for screening purposes, gives a very fine focus with only a few milliamperes

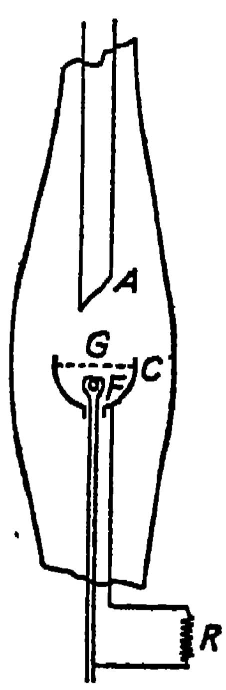



Fig. 156.—Müller Three-electrode Tube.

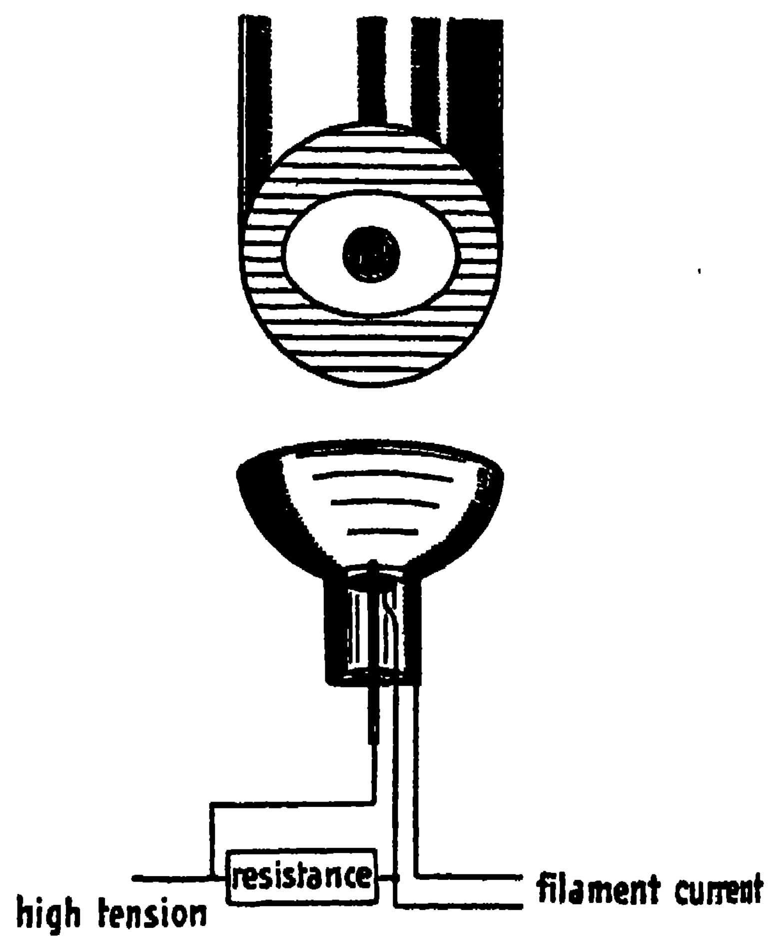



Fig. 157b.

of current. For radiographic work a much higher current is often desired (up to as much as 100 milliamperes) to allow flash exposures, for example, for thorax radiography. Such a tube cannot be sharply focussed, as in this case the electron stream is confined to a small area of the tube target, which becomes overheated and the tube is destroyed by fusion of the focal spot and evaporation of tungsten. To overcome this difficulty of utilising the tube for two really distinct purposes, bi-cathode tubes have been produced in which one cathode is so constructed as to give a fine pencil of electrons upon the target for screening purposes and the other cathode to give a broad focus for radiography with heavy currents.

The practical difficulty of this method is the inconvenience of changing over the cathode high-tension lead by means of a high-tension switch. Whilst this is being carried out a carefully posed patient may move.

Müller has very ingeniously overcome the difficulty of fulfilling

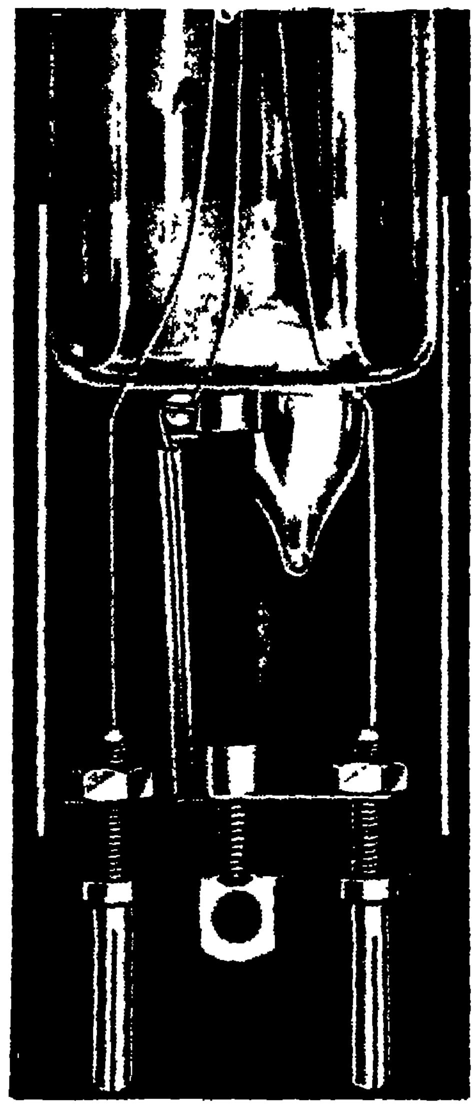


FIG. 157A.—Details of Müller " Autofok " Tube.

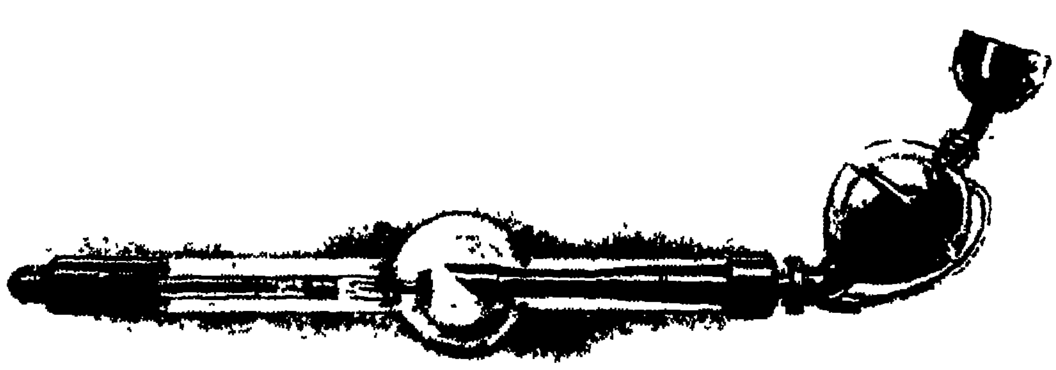


FIG. 158.—Müller " Autofok " Tube (Messrs. Müller).

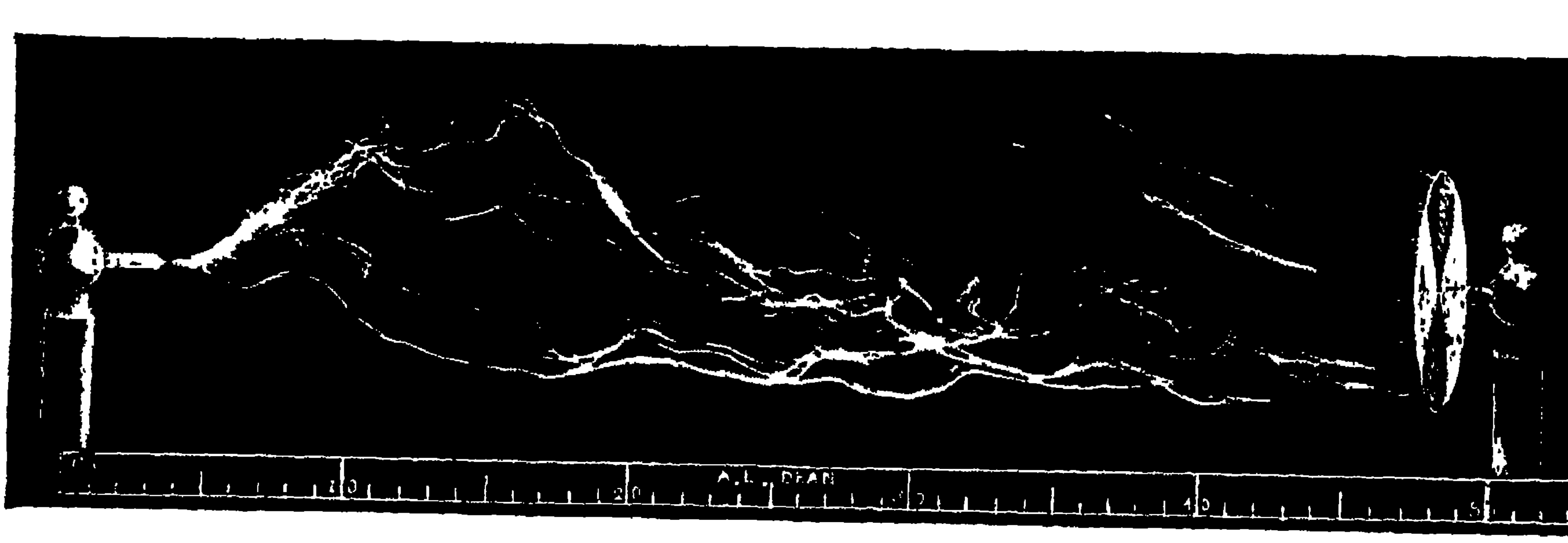


FIG. 159B.—Spark Discharge.

[To face p. 190.

these contrary requirements in his " Autofok " tube. This tube has a third electrode, the function of which is a controlling action, very similar to the function of the grid in the now well-known three-electrode wireless thermionic valve.

Within a spiral filament (Fig. 157B) is an insulated auxiliary electrode of rod form. If this electrode is given a negative potential with respect to the filament it will tend, by electrostatic influence, to more or less broaden the pencil of electrons passing from cathode to anode. As a result the cathode ray beam will encounter a larger target area. Thus the target is raised to a lesser temperature, and overheating and fusion is less likely to occur.

To give this electrode a negative potential with respect to the filament a high resistance is inserted and a circuit formed between the auxiliary electrode and the cathode. The negative wire of the high-tension lead is led directly to the auxiliary electrode, current can go to the filament and thus through the tube only after passing this resistance. Assuming the ohmic law $E = RI$, then if the resistance is 10,000 ohms and the tube current 100 milliamperes, the voltage at the auxiliary electrode will be 1,000 volts more negative than the cathode. This will result in pressing away the negative electrons from the centre of the cathode ray pencil and thus causing a larger area of their impact upon the target.

At half this tube current, *i.e.*, 50 milliamperes, the auxiliary electrode has a negative potential of 500 volts with respect to the filament. The cathode ray pencil is therefore less extended and the resulting focal spot correspondingly smaller.

At a low current of say 5 milliamperes the opposing negative potential will only be 50 volts, thus having a comparatively small effect, so that in consequence of the general design the focus will be made a very fine one.

The variations of focus from fine to broad as the current *viâ* the tube increases is therefore automatic and inherent to the tube owing to this ingenious device. Such a tube is shown in Fig. 158 designed to work up to 90 kv.

## VALVE TUBES

Valve tubes, like X-ray tubes, are of two types, (*a*) ionic (*b*) electronic.

The uses of such tubes, which tend to become mainly of the electron type, are ;—

(1) To suppress " inverse current," in induction coil apparatus.

(2) To suppress the reverse half-cycle in alternating current diagnostic apparatus. This application is small, as an electron X-ray tube is itself essentially a valve and, if the load is not too great, can itself suppress the undesired half-cycle, without the further aid of a valve tube (p. 343).

(3) To suppress alternate half-waves in continuous potential apparatus (p. 354).

(4) To rectify half waves of alternating current (p. 343).

To appreciate the ionic type of valve tube we must first consider the simple unsymmetrical electrodes often and still used in the older coil outfits to suppress inverse current.

If a plate-and-point spark gap is observed in open air, it will be seen that when the point is positive the discharge passes directly to the centre of the plate but, when the point is negative, the spark passes to the edge of the plate (Fig. 159A). Use of this fact allows the current direction to be determined.

The physical explanation is as follows ; When the point is positive the passage of the discharge is preceded by the emission of electrons from the negative plate by virtue of the applied potential. These electrons cause shock ionisation of the intervening gas, and there is therefore an outgrowth of ionised air from the plate. It follows that, as the direct path from the centre of the plate to the point is smallest, the ionised gas from the plate will first meet the point electrode at its point and a central discharge occur between point and plate centre.

When however the plate is positive the electrons are emitted from the point electrode and, travelling to the plate electrode, give rise to electro-

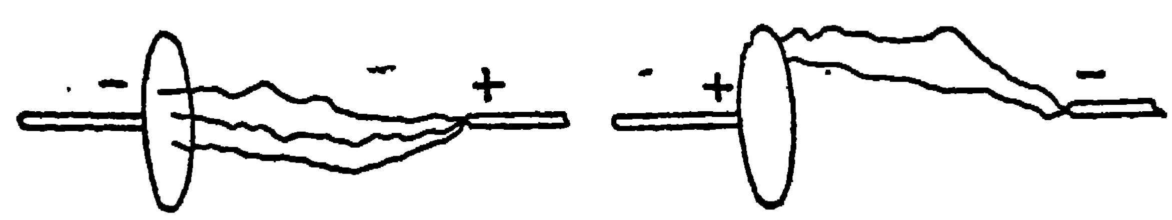


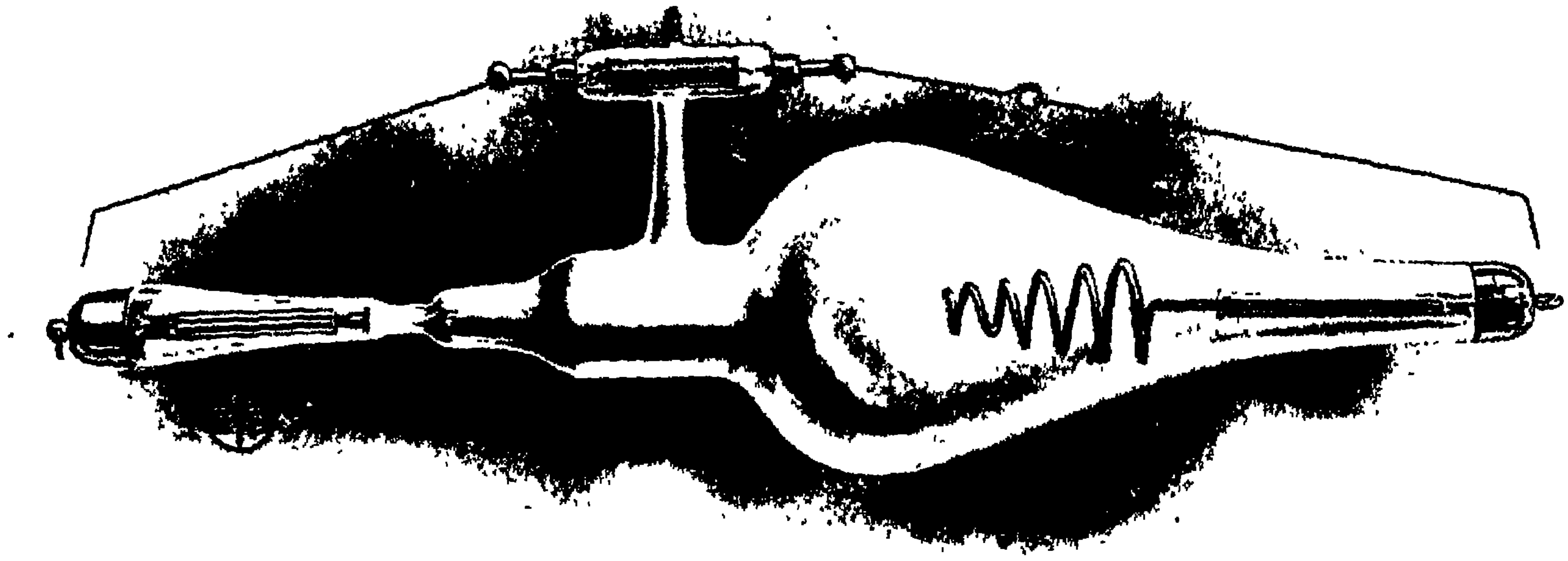

FIG. 159A.

static tubes of force between the two electrodes. As these grow at the centre their mutual repulsions drive them from the centre to the periphery where the concentration is at first small, but, as the process continues (and if the applied potential is sufficient) the concentration of tubes of force at the periphery becomes so great that the phenomenon of brush discharge (Chapter I., Vol. I.), occurs. This results in the air at the neighbourhood of the periphery becoming ionised. This ionisation grows from the edges of the plate until the point electrode is within the ionised atmosphere, and a discharge results from point to the plate edge. As the variation of electrostatic stress occurs at various points of the periphery so will irregular, and usually multiple discharge, occur (Fig. 159B.)

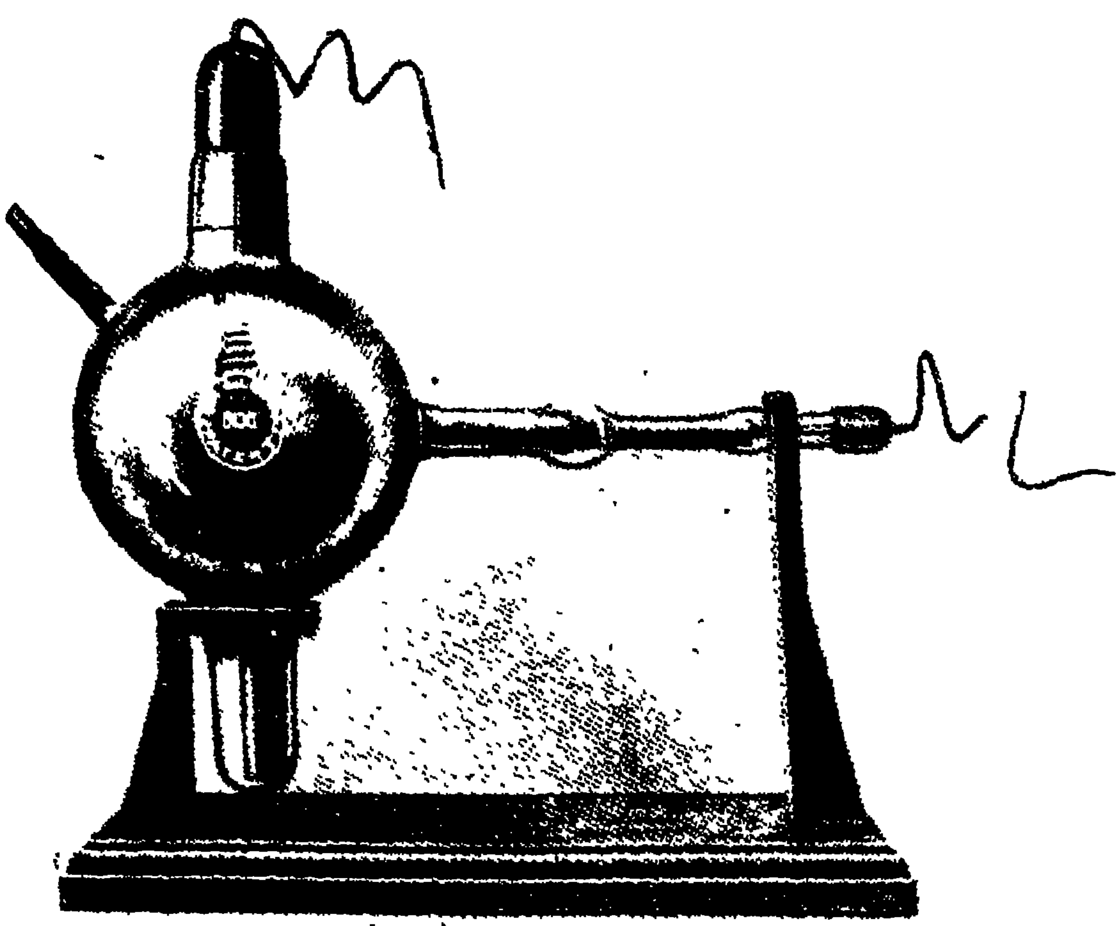
As ionisation more easily occurs when the point is negative and, the concentration of electrostatic stress being greater, more electrons are easily emitted, there will be a greater tendency for a discharge to pass from point to plate than *vice versâ*, *i.e.*, the gap tends to rectify the discharge by suppressing voltages directioned from plate to point, particularly if these are of lower value, as in the case of induction coil " inverse voltage."

The disadvantage of this cheap and effective but uneconomic form of rectifier is the noise it occasions. Duddell * introduced a more steady and

* *Jour. Rönt. Soc.*, 4, p. 100, 1908.



(*a*) Villard Type.



(*b*) Lodge Type.

FIG. 160.—Ionic Valve Tubes (A. E. Dean).

[*To face*

less noisy form of rectifier by utilising an insulated point within the centre of a sphere.

All such spark-gap rectifiers are very inefficient. A more stable form is produced by use of a wire electrode at the centre of a cylindrical electrode (as in some forms of electron valves) when current passes more easily from wire to cylinder than *vice versâ*, due to ionisation of the intervening air by brush discharge from the wire, when this is negative. A still better solution is not to use a single long gap, but a series of small plate and point gaps, when the discharge is far less noxious as regards noise and more regular in operation. Such an arrangement tends to the noiseless " quenched-spark " type of multiple gap (Chapter IV., Vol. I.). Dessauer has used such enclosed multiple spark gaps to prevent flow of inverse current.

A further method of decreasing the noise is to enclose the gap in a more or less sound-proof cylinder (Fig. 63). In the Schreus " Automat " this form of gap has been utilised to permit of automatic regulation.

It is only a step from this enclosed spark gap to exhaust the enclosing vessel and, by so rendering the discharge more difficult, to permit of the sparking distances being conveniently reduced and the discharge made more regular, as the gas does not so rapidly vary. The use of such valves is associated with the names of Hittorf, Villard and, in England, Lodge.

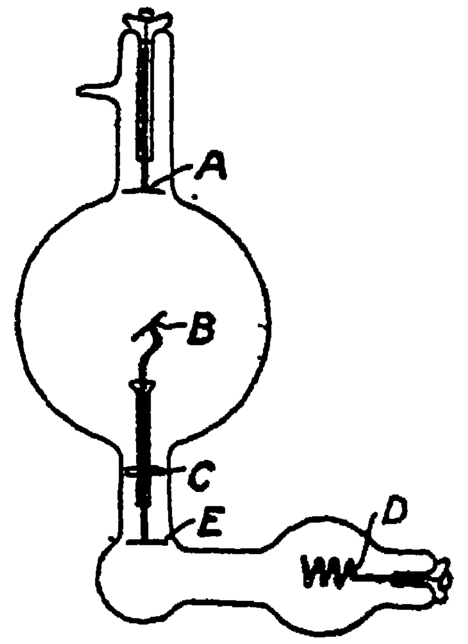


FIG. 161.—Cossor Combined X-ray Tube and Valve.

In such forms of ionic values (Fig. 160) two asymmetric electrodes are used, such as a point and a spiral electrode. The pressure of the gas, usually hydrogen, is reduced to about 12 bars, until the pointed anode is entirely within the Crookes dark space of the cathode, *i.e.*, the region where ionisation does not occur.

Such valves are very subject to pressure variations and are usually fitted with some form of softening device, as in the X-ray tube. Apparent hardness of an X-ray tube, in circuit with a valve tube, may often be traced to a hard valve tube.

The fall of potential across such valve tubes is of the order of several kilovolts and, the inclusion of a large number of such valves in series, in a large induction coil circuit to suppress inverse current, results in such a loss of effective potential across the X-ray tube that the use of a smaller coil with less inverse current is often to be preferred.

Such valves only function efficiently below 45 kv. and with 20 to 30 milliampères at the most. For heavy " flash exposures," a number must be connected in parallel. Irregularities then occur, due to variations of voltage across the particular tubes of varying hardness. To overcome

this and to keep the pressure more stable, multiple valve tubes having the separate containers in direct communication are often utilised.

Cossor (Brit. Patent 3,106/1905) has employed a combined X-ray tube and valve tube with separate electrodes (Fig. 161).

Sterzel (Brit. Patent 14,196/1905) has employed a special tube (Fig. 72) in which the anode has two oppositely directioned targets, one an active target as regards X-ray production and the other an inactive electrode in this respect. The tube has two cathodes, one of which acts as cathode to the target to excite X-rays upon one half-wave of an alternating current, and the other, as cathode to the non-X-ray producing target, so acting as a valve rectifier for the other half-cycle of the applied alternating voltage. Such a tube can be directly connected to an alternating source

Two other methods of rectification of alternating energy should be mentioned, namely the mercury vapour arc and the alkaline electrolytic cell. These are however only suitable for low voltages of 10 kv. and 5 kv. respectively and have no practicable application to X-ray purposes.

Kohl * has suggested the use of such electrolytic cells, able singly to rectify 500 volts, but their great capacities render them unsuitable for the small currents of radiological apparatus.

What is essentially a valve tube is employed in the oscilloscope (*q.v.*, Vol. I.) in which the variation of length of the Crookes dark space with variation of voltage is, by rotation, used to give a record of voltage variation with respect to time.

With the nearly universal use of transformer apparatus, instead of coil apparatus, the use of ionic valves tends to disappear.

The ionic rectifier has, of recent years, been nearly totally replaced by the thermionic rectifier, capable of handling enormous amounts of energy, for example valves have been produced, often of metallic construction, capable of handling 500 to 1,000 kw.

Until recently the voltage of these valves, of American origin, has usually been limited to about 100 kv., but German examples now exist capable of dealing with deep-therapy voltages of 225 kv. and over 300 m.A.

This type of rectifier is essentially a heated filament surrounded by some form of plate electrode. When an alternating voltage is applied that half-cycle which renders the heated electron-emitting filament negative is allowed to pass, whereas that half-cycle which renders the cold " plate " electrode negative is suppressed, as electrons are not present to form the passage of current. For heavy powers, or high voltages, the difficulty of production is chiefly due to the very large electrostatic attraction between the mechanically weak filament softened by heating and the rigid plate, which tends to draw the former to it.

To minimise this attraction the majority of such valves have a heated spiral filament placed concentrically to the cylindrical plate

* *Zeits. für Elektr.*, 1909.

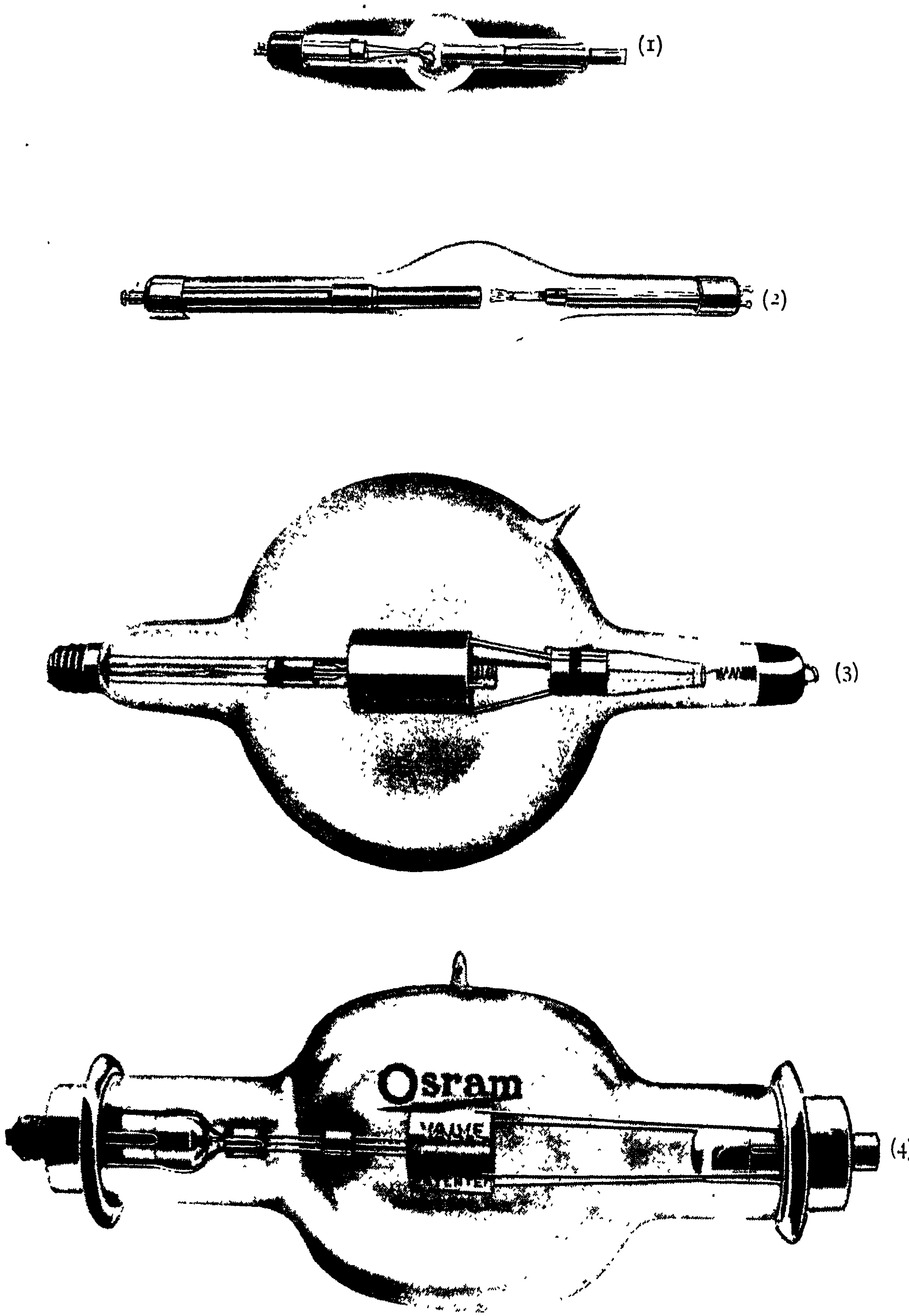



FIG. 162.—Electron Valve Tubes. (1) Müller tube, 90 kv., 300 milliamperes (400 milliamperes for short period). (2) Müller tube, 227 kv., 300 milliamperes (400 milliamperes for short period). (3) Cossor tube, 75 kv. capacity load, 100 milliamperes; 150 kv. resistance load, 100 milliamperes. (4) G.E.C. tube, 75 kv. capacity load, 100 milliamperes; 150 kv. resistance load, 100 milliamperes.

[*To face p.* 195.

(Fig. 162 (3) and (4)), so that the attraction upon the filament in one direction is neutralised by the attraction of the opposite positioned portion of the plate in the other direction. Also to protect the filament, valves have been built upon the principle of the protected Lilienfeld X-ray tube filament. Such valves have a tungsten filament, and the power at which they operate is only limited by the temperature and filament surface and the resulting possibility of the filament supplying, from its limited surface, sufficient electrons to permit the passage of the desired currents For very high voltages the filaments are best heated by special insulated dynamos. Should a highly peaked voltage be supplied, if the heated filament cannot supply sufficient electrons to allow passage of current at the higher peak values, such valves will tend to "smooth out" the peaks of the voltage curves. If used with induction coils there is a great tendency in this respect unless the filament is greatly overheated.

Unlike in the X-ray tube, the greatest stress on the glass envelope in these valves is not in the region of the cathode but in the region of the anode, where fluorescence may occur when the passage of current is prevented and the greatest stress is then exerted. This danger occurs since normally the applied potential is utilised in the transport of electrons from the filament. When, however, the valve is operated above the filament "saturation" value, *i.e.*, where the filament at the given temperature is unable to supply the necessary number of electrons, the applied potential besides effecting the transport of electrons causes acceleration of the electrons. These then bombard the plate anode and render it incandescent so that occluded gas is disengaged giving a characteristic fluorescent region around the anode. The anode also then gives rise to thermo-electrons, so that rectification no longer occurs and destruction of the filament or the glass wall results owing to electronic bombardment by reverse current. Whilst excessive heating of the filament shortens the life of a valve under heating, as shown by the anode glow, is still more dangerous and may result in immediate destruction. The valves are rendered more safe if they are oil-immersed.

If valve tubes are left in circuit when the energy is not being absorbed, for example by an X-ray tube, there is a very great risk of the valve exceeding the filament saturation current value, with resulting destruction of the filament.

For polyphase voltages multiple anode tubes with a common filament are used, for example, a three-phase valve would have a single common filament and three separate cold anodes.

Müller produces a valve for X-ray purposes which requires to heat the filament 7 to 8 amperes at 11 to 12 volts, when working at 200 kv. Whereas with a steady current such valves would allow the passage of a saturation current of 300 milliamperes, the practical limit with induction coils is

about 60 milliamperes in consequence of the necessity of over-heating the filament to ensure the current and voltage curve is not smoothed out, or the valve overloaded, during the intense intermittent coil discharges. For a sine form alternating current the value varies between 100 and 150 milliamperes, since the valve must be able to deal with the high peak value and not the mean square value shown by a current-measuring instrument. Such valves cause a voltage drop in the circuit of 1,000 to 1,500 volts for these high working conditions, values very much smaller than those of the best ionic valves working at much lower voltage and current values.

In working with all valve tubes it should be always remembered that these are essentially inefficient X-ray tubes, and if not enclosed by protective material may give rise to fogging of plates, etc., in spite of the aluminium of the electrodes only forming a very inefficient target. The light to which they give rise, objectionable during fluoroscopy, is easily prevented by the use of such protection, or even a dark cloth.

Also like X-ray tubes, the electron stream from cathode to anode is very liable to deviation from the anode, by the presence of magnetic fields, with resulting heating and fracture of the glass container.

As the transformers used to heat the valve filaments are usually of the open magnetic path type, with much stray magnetism, this danger is a very real one, and valves and X-ray tubes should always be located away from such strongly magnetic apparatus by at least 1 meter, or, even better, shielded by a suitable metallic shield. Utilisation of this deviation was made by Caldwell (Brit. Patent 29,839/1912) in the older ionic valves, who to soften such a valve, introduced a magnetic coil into a re-entrant part of the tube, so deflecting the cathode stream upon and to heat a suitable softening material as sodium formate.

## EXERCISES ON CHAPTER III

*Questions 1 to 8 are based upon analogous questions set in the D.M.R.E. Examinations of Cambridge.*

(1) Show diagrammatically the relation between the temperature of a Coolidge tube filament and its thermionic emission. Discuss the practical results. Compare the relative advantages of supplying the Coolidge filament by (*a*) accumulators, (*b*) a transformer.

(2) Describe some type of hot cathode X-ray tube and the basic phenomena. How is the current dependent upon (*a*) the applied potential difference, (*b*) the heating current of the filament? Discuss the merits and demerits of various methods of heating the filament.

(3) Describe the Coolidge tube and its basic principles. What are its merits as compared to the ionic tube? The output of a Coolidge tube is found not to be directly proportional to the current passing through it. How do you explain this?

(4) Explain the action of the electron tube. What are its merits and demerits ? What condition must be observed in order that it rectifies its own current ?

(5) Describe the phenomena of thermionic emission and indicate the basic difference of operation of the gas and Coolidge tubes.

(6) What is the relative efficiency of the gas and Coolidge tubes ? With a constant filament current, how does the current *viâ* a Coolidge tube vary with the potential difference across its electrodes ?

(7) What is " shock ionisation " and what is its action in the gas tube ? Describe the difference of conduction in (*a*) a gas tube, (*b*) an electron tube.

(8) Give the relation between filament current and potential in an electron tube and state how this is explained upon the electron theory. Discuss an analogy of electronic emission and evaporation of water.

(9) If the heating current (either from a rotary converter or accumulator) should fail in a Coolidge tube outfit, to what faults might it be due and how would you trace them ? (Soc. of Rad. Exam., December, 1922.)

(10) What are the essential points of difference between a " Coolidge tube " and a " gas tube " ? (Soc. of Rad. Exam., June, 1925.)

(11) For a prolonged treatment the milliamperemeter is set at 3 milliamperes, the voltage being 200,000, as measured by a spark gap. The Coolidge filament is heated by a transformer. The milliampere reading suddenly rises to 4. What are the possible causes and how would you discover and rectify them ? (Soc. of Rad. Exam., January, 1922.)

(12) What is inverse current and how is its presence indicated ? (Soc. of Rad. Exam., July, 1922.)

(13) Describe the cathode of an electron tube. What factors modify the focus ? How can such a cathode be made self-focussing ?

(14) Describe the advantage and disadvantage of a linear focus tube.

(15) Contrast the accumulator, rotary-converter and transformer methods of supply the filament of an electron tube.

(16) Describe the construction and action of the Lilienfeld tube.

(17) What is auto-electronic emission ? Discuss its use to excite X-radiation.

(18) Discuss the various uses of a third electrode in an electronic X-ray tube.

(19) What technical difficulties arise in the production of metal X-ray tubes and how are these overcome ?

(20) Describe the mode of action of valve tubes of both the ionic and electronic types.

(21) What are the advantages of a metal X-ray tube ? Describe such a tube.

(*b*) transformers with direct, or electrostatically coupled, circuits (auto-transformers),

of which, class *a* is the most important.

The simplest form of transformer, originally due to Faraday, consisted of an iron ring on which an alternating current coil, or primary, was wound in one part, so creating a magnetic field in the iron ring, which in turn induced a voltage in a second winding, or secondary.

Such a simple ring transformer is not used in practice, partly owing to difficulties of winding a ring with a very large number of turns of conductor, partly because such a ring is not easy to laminate, and for a number of other technical reasons, as efficiency of transformation, etc.

Similar to such a primitive transformer we have in all cases ;

(1) A primary winding.
(2) A magnetic circuit.
(3) A secondary winding.
(4) A dielectric circuit, surrounding and insulating the above.

We have therefore in the design of transformer apparatus to consider ;

(*a*) The magnetic circuit.
(*b*) The conductive or electrical circuits.
(*c*) The dielectric circuit.

The relative arrangements of the conductive electric and the magnetic circuits leads to various types of transformers, all of which are modifications of ;—

(1) *Core type* (Fig. 164A), in which the windings surround the magnetic core.

(2) *Shell type* (Fig. 164B), in which the magnetic circuit surrounds the windings, as in a shell.

Variations of these fundamental forms occur ; for example, a well-known type of transformer is that of Berry, which may be considered as a group of component core-type transformers arranged as a shell type. As these are not used in high-voltage X-ray transformers, they need here no further description.

An alternative classification of transformers is as *closed core* and *open core* types. Of these the former has a closed iron circuit and is the type generally used in alternating current work and the latter is represented by the induction coil, which can equally be used with alternating current as with interrupted direct current.

Transformers may again be wound (*a*) *concentrically* (Figs. 164A and 164B) (*b*) *sandwiched* (Fig. 164C). The former is the type of winding most suitable for high-voltage work, as X-ray transformers, since the primary and secondary are more easily insulated when both coils are wound concentrically around the long axis of the core. In the sandwiched type, primary and secondary are wound in flat coils and mounted upon the core alternately. Such transformers are unsuitable for high-tension work, in con-

sequence of uneconomical insulation between each sandwiched coil and difficulties of connection, due to proximity of high and low tension leads.

Concentric windings may be wound in *layers* or in *sections*.

The advantages of the core type of transformer, as compared to the shell type are ;—

(1) Small weight of iron for the magnetic circuit.

(2) Small length of wire per turn, in either primary or secondary

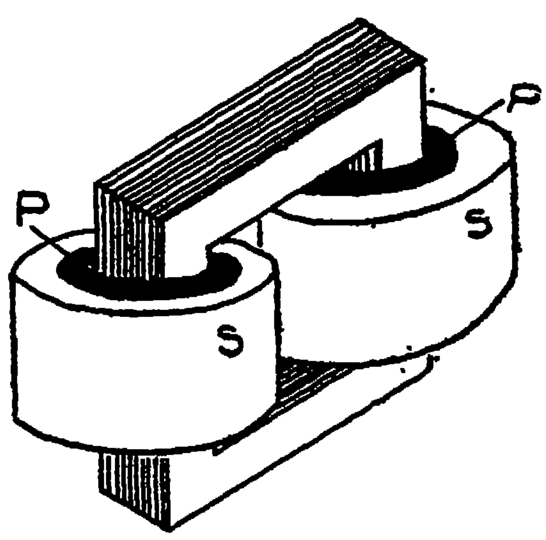



FIG. 164A.

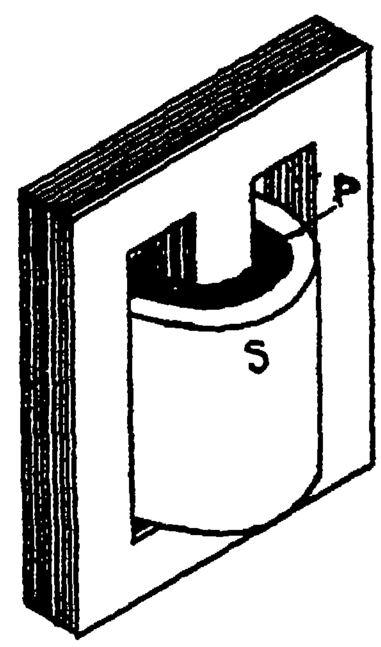



FIG. 164B.

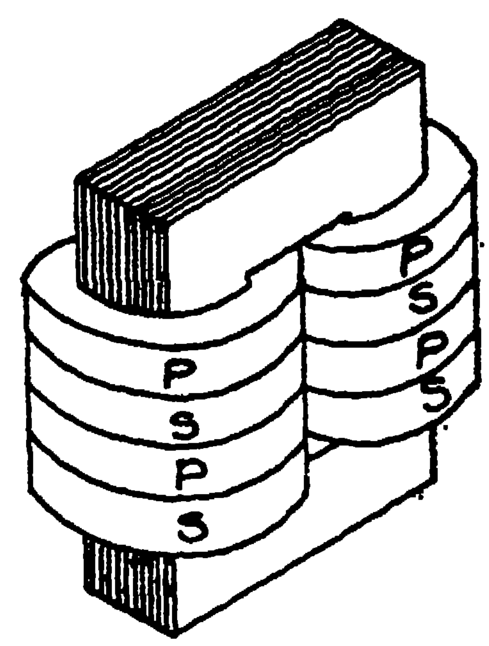



FIG. 164C.

Types of Transformers.

winding, and hence lower cost, with greater efficiency, in consequence of smaller total resistance.

(3) Accessibility of windings, of particular importance in highly insulated high-tension transformers.

(4) Better radiation of heat developed during use and, for high-tension work, less danger of breakdown due to insulation heating.

Disadvantages of the core type are ;—

(1) Large length of magnetic circuit, hence greater magnetic losses due to hysteresis and eddy currents.

(2) Greater number of secondary turns owing to the area of the core being limited, so that the magnetic flux enclosed per turn is limited. For a given wire this results in a greater resistance, In practice this can be easily overcome by selection of a stouter wire and actually in X-ray transformers even the smallest convenient wire (32 to 40 S.W.G.), is sufficient since the current is nearly negligible.

It follows in all cases from the ratio $\frac{E_1}{E_2} = \frac{n_1}{n_2}$, since the energy is proportional to the product of voltage and current, and since the energy must necessarily be lower in the secondary circuit, by the principle of the conservation of energy, then a great increase of voltage from $E_1$ to $E_2$ must result in a great decrease of current $C_1$ to a small value $C_2$, such that

$E_1C_1 = E_2C_2$, the power factor (see p. 124, Vol. I.) of each circuit being assumed as the same.

## FUNDAMENTAL THEORY OF THE TRANSFORMER

If we consider an alternating current winding, wound upon an iron circuit of area A and induction B, then the total number of lines of force N varies from $+ N = BA$ to $- N = - BA$, (or as shown in Fig. 165 from $+ \phi$ to $- \phi$ where $\phi = N$), as the magnetising current varies harmonically from its maximum values $+ I$ to $- I$.

Considering the magnetic variation only, then for any turn of winding ;—

$$E = \frac{dN}{dT} = \frac{\text{rate of change of flux}}{\text{rate of change of time}}$$

and, if the frequency of alternation is $\eta$, the flux must change from its

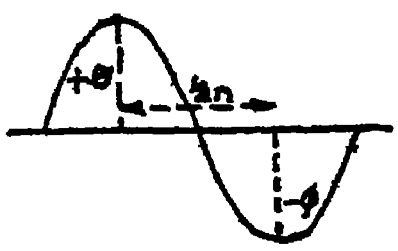


FIG. 165.

value $+ N$ to value $- N$ in half the time of $\frac{1}{\eta}$ second (Fig. 165), the rate of change is therefore—

$$\frac{2N}{\frac{1}{2\eta}} = 4N\eta$$

Since we define the *Maxwell* as the change of $10^8$ lines of force giving rise to an induced voltage of 1 volt, then $E = \frac{4N\eta}{10^8}$ volts, per turn ;

or for $n$ turns ;

$$E = \frac{4N\eta n.}{10^8}$$

This is true for a voltage variation in which the *form factor, i.e.*, $\frac{\text{root mean square value}}{\text{mean value}}$, is unity (see p. 135, Vol. I.), as in the case of a rectangular type of voltage wave. For a pure sine wave, to which we tend in normal alternating current machinery, the form factor is 1·11. Therefore, since our instruments usually read mean square values, and we are actually dealing with mean induction variations, we must introduce the form factor $f$, *i.e.* ;

$$E = \frac{4fN\eta n}{10^8} \text{ volts}$$

$$= \frac{4{\cdot}44N\eta n}{10^8} \text{ since } f = 1{\cdot}11.$$

This equation is the fundamental equation of all transformer design. It is easily seen to apply both to the primary and secondary circuit, as

the value $N = BA$ is necessarily the same for both, *i.e.*, we may obtain the usual transformation ratio since ;

$$\frac{E_1}{E_2} = \frac{\dfrac{4\cdot44\ BAn_1\eta}{10^8}}{\dfrac{4\cdot44\ BAn_2\eta}{10^8}} = \frac{n_1}{n_2}$$

In practice, as we more usually in England deal with inches than centimetres, it is of use to convert this formula to values of B and A corresponding to square inches, whence ;—

$$E = \frac{1}{3\cdot49}\ \frac{BA\eta n}{10^8}.$$

or, still more usefully, to consider the "volts per turn," *i.e.*, $\frac{E}{n}$, where ;

$$\frac{E}{n} = \frac{1}{3\cdot49}\ \frac{BA}{10^8}\eta,$$

B and A now being lines of induction per square inch and area of core in square inches respectively.

## METHODS OF COOLING TRANSFORMERS

In any transformer we have various energy losses, of which the most important are ;—

(1) Losses due to heat formed by passage of current in the conductors, known as the *ohmic or copper loss*.

(2) Losses in the magnetic circuit due to magnetic hysteresis and eddy currents. These also appear as heat and are known as *iron losses*. For low frequencies the hysteresis loss is the most important but, at higher frequencies, the eddy current loss may be the most important.

(3) Losses due to dielectric hysteresis. For lower frequencies these are nearly negligible, and only become of importance at higher frequencies.

(4) Losses due to the straying of magnetic flux from the core, so that some lines do not cut both circuits. This leakage current is usually small in a well-designed transformer.

Of these losses (1) to (3) all appear as heat, and as we have closely wound windings it becomes of importance to aid the removal of this wasted energy to avoid injury to the insulating materials.

The methods available in general are ;—

(1) *Air cooling*, in which air ducts are left in the windings and core, through which air circulates and carries heat away by convection.

(2) *Forced air-blast*, which is essentially as (1), but air is driven by fans more rapidly *viâ* the ducts.

(3) *Oil Cooling.*—The transformer is all immersed in oil. This absorbs heat from the windings and core and conveys the heat energy to the metal container, which radiates it into the air. The radiation may be facilitated by increasing the tank surface area by means of pipes in which the ratio of volume of oil to area is decreased.

(4) *Oil-water Cooling.*—This is essentially as (3), but metal pipes are immersed in the oil and cold water is pumped *viâ* the pipes, so cooling the oil which, in turn, cools the transformer. This method is only used for heavy power transformers and is not needed for X-ray transformers of high voltage but low energy. This method has been used to cool oil-immersed X-ray tubes (see p. 122).

X-ray apparatus transformers are of both the air and oil cooled types The latter are largely superseding the former. One may say that the older X-ray transformers of comparatively low energy value are air-cooled, but the modern heavier transformer is invariably oil-cooled.

*The Air-cooled Transformer.*—The air-cooled transformer requires an overall increase of volume since, to promote efficient cooling, large air ducts have to be provided. Larger clearances have also to be allowed in order to overcome " corona," which is practically non-existent when the apparatus is oil-immersed.

It is questionable whether it is a practicable or economic proposition to design transformers to give secondary voltages of 250,000 volts and more, as now used in deep-therapy radiology.

Air-cooled transformers have given good service over extended periods at secondary voltages claimed to be as high as 125,000 peak volts for X-ray purposes, but this should be contrasted with the fact that transformer designers, familiar with all types of transformers, hesitate to use air cooling only above 11,000 volts, and even with forced-draught air cooling, above 33,000 volts.

The inference is therefore that such X-ray air-cooled transformers are worked at a dangerously low factor of safety of insulation.

Of equal objection to the use of air cooling for high-tension X-ray transformers is the fact that the open cooling tends to the accumulation of dust and dirt in the windings. Such foreign bodies disturb the electrostatic field distribution and tend towards breakdown of insulation. With forced-draught air-cooling it would be essential to filter thoroughly all the air before it were allowed to enter the windings. In the air-cooled transformer the dimensions of the core and windings are largely determined by the heat generated in these structures, the insulation of which renders them bad conductors. Since, for any appreciable power, these surfaces are usually inefficient, it becomes imperative to work with smaller current and magnetic densities, to decrease the heat production. As this increases both space and cost, the air-cooled transformer rapidly tends to impossible values at very high voltages.

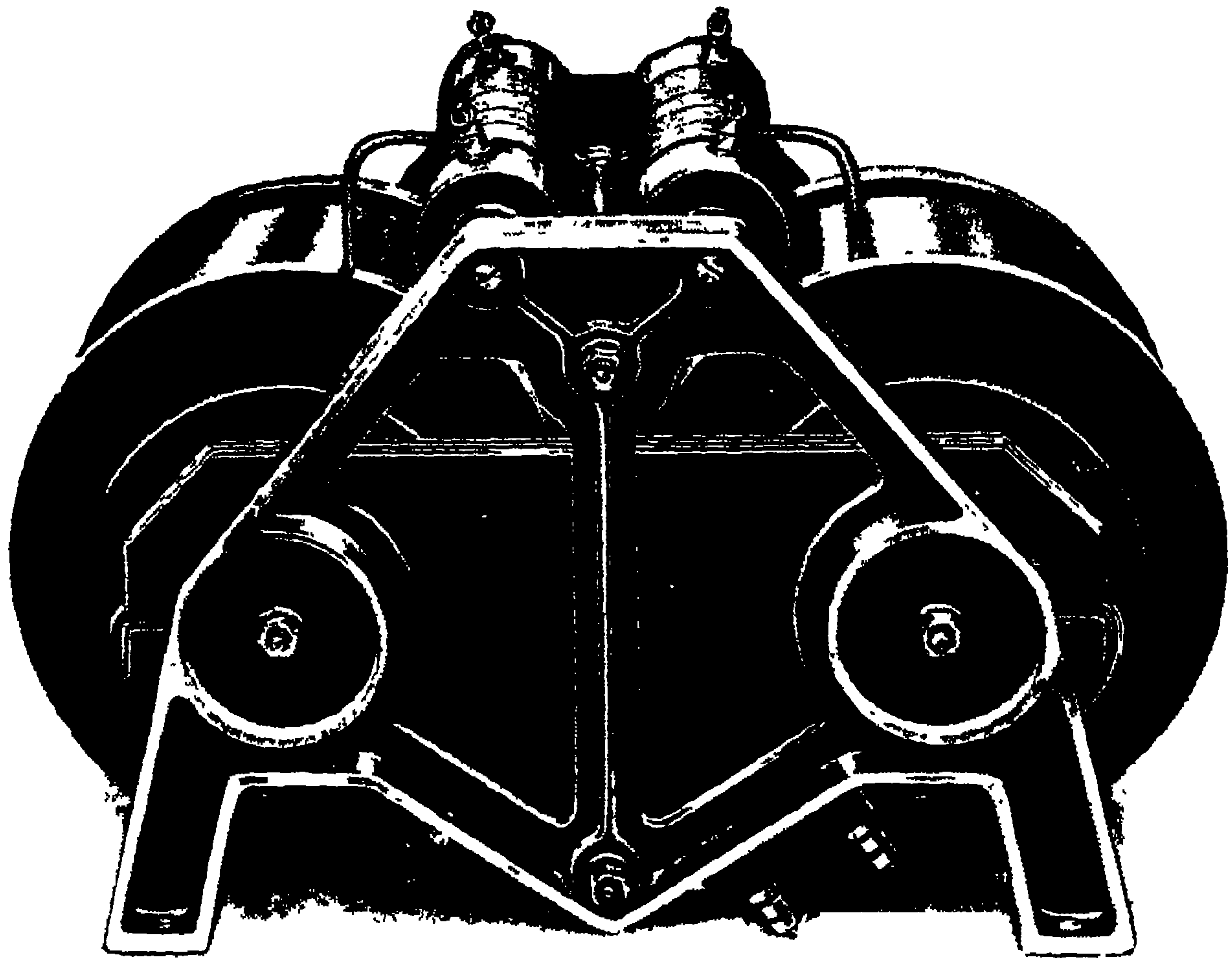


FIG. 166.—Air-cooled X-ray Transformer. The protective choke coils are seen above.

As a further disadvantage of the air-cooled transformer, one may mention that the dimensions of all air-cooling channels must be increased.

We have seen (p. 33, Vol. I.) that the distribution of electrostatic stress over a composite dielectric is inversely as the specific inductive capacities.

As a consequence, when we utilise any given insulating medium, say of S.I.C. = 5, with air = 1, all air distances must, to ensure even distribution of the electrostatic field, be as 5 of air to 1 of medium, whereas with oil of S.I.C. = 2, these clearances need be only as 2 to 5, *i.e.*, two and half times smaller. As a consequence, since the dimensions of, for example, the heavy insulation between primary and secondary must be much greater with air, the average value of length per turn of each winding increases. The length and resistance of the windings so increase, resulting in further heat production and lowered efficiency. Even when such clearances are allowed, there is a difference in behaviour of air and oil when between high potential windings. To take a concrete case, two adjacent turns of a transformer secondary winding ½ in. apart in air begin to give visible corona at 30,000 volts. Immediate breakdown may not result, but the heat effect of the corona is to destroy gradually the insulation, so that small values of corona discharge will sooner or later cause breakdown by deterioration of insulation. With oil insulation however, corona does not occur with the same windings until 60,000 volts, corona production and breakdown being nearly simultaneous, so that, working at lower values, say 30,000 volts, corona may be considered as entirely absent and no allowances need accordingly be made.

When therefore oil-cooling offers such insulation advantages allowing reduction of cost, size, and greater efficiency, there appears to be no obvious reasons for the use of air-cooled transformers for high voltage X-ray transformers, working at values which are a large multiple of the values usually considered as safe in normal transformer practice.

Having now considered the general features of transformers, it will be of value to consider the design of a typical X-ray transformer in detail, and so to illustrate the various factors which come into consideration, and which determine its subsequent operation.

The purely medical radiologist may consider that such subjects are beyond his concern, but it should be recognised that such matters are more his concern than the concern of the manufacturer, who can otherwise substitute an inferior article at a high price. In all cases the medical radiologist is directly or indirectly the purchaser (who is the most concerned), and it is only by the radiologist appreciating the requirements and insisting upon a properly designed apparatus that we can expect any technical progress in X-ray apparatus, much of which at the present day

appears to be designed by haphazard methods, rather than by any real knowledge.

It is often stated by the X-ray manufacturer that a properly designed transformer would occupy more space and be more expensive. The increased space is small and is usually easily obtainable. The prices charged for properly constructed transformers are usually less than prices charged for many of the shoddy transformers of X-ray technology.

It becomes more and more necessary for the medical radiologist to have a working knowledge of transformer design, so that he abandons the practice of buying something *en bloc* in a case, but instead insists in getting an efficient and safely constructed apparatus, capable of operation without breakdown over an extended period.

## THE CORE

The core of a transformer will necessarily vary in cross section in proportion to the energy which it transforms for any given frequency. It will also vary according to the frequency, a subject with which we will deal at length later.

The relative proportioning of the core dimensions is a matter of empiricism, based upon practical experience.

The area of cross section, or actually, the diameter D, is fixed by the output and may be determined by the relation ;

$$D = 2{\cdot}25 \times \sqrt[4]{\text{kv.a.}}$$

thus, for 10-kv.a. and 5-kv.a. instruments, D is 4 in and 3·5 in. respectively, a result, seen to be independent of the primary or secondary voltage, and only dependent upon energy considerations.

Having fixed the core area, since the induction per unit area is fixed by the particular magnetic material available (either soft iron, Lohy's steel, or stalloy) the volts per turn are determined. It is therefore only a matter of accommodating the length of core, to carry the desired number of total secondary turns, when the depth of the winding has been determined by the permissible volts per secondary coil section being limited to about 5,000 volts per section.

Considering the dimensions shown in Fig. 167, if we make L large we obtain a long core, each turn of which has relatively a small length and therefore small resistance. The increase in length of the core also allows the sectional coils to be well insulated from each other. The objection to a very long core is that, particularly when the cores are arranged horizontally, the construction is mechanically weak and the core is liable to sag by the weight of the windings.

On the other hand, if we make L short we obtain a very robust type of transformer, but to insert the necessary number of insulated secondary

windings upon the core, these must be very deeply wound, with resulting bad ventilation as regards heat development. Also the outer turns have a very long length and large resistance for a very small voltage increase, since the magnetic field in which they are situated falls off rapidly with the increase of distance from the core. (Compare "The Induction Coil.")

There is an intermediate value between these two limits which, for power transformers, is usually given by L = 4D, where D is determined as above. As the power of high-tension X-ray transformers is usually comparatively small and the prime consideration is the suitable insulation of the windings, this relation is more conveniently increased to L = 5D or 6D, this increase being further warranted since, generally, an X-ray transformer, unlike a power transformer, is not likely to be perhaps operated under mechanical vibratory conditions, so that mechanical considerations of rigidity are of less importance.

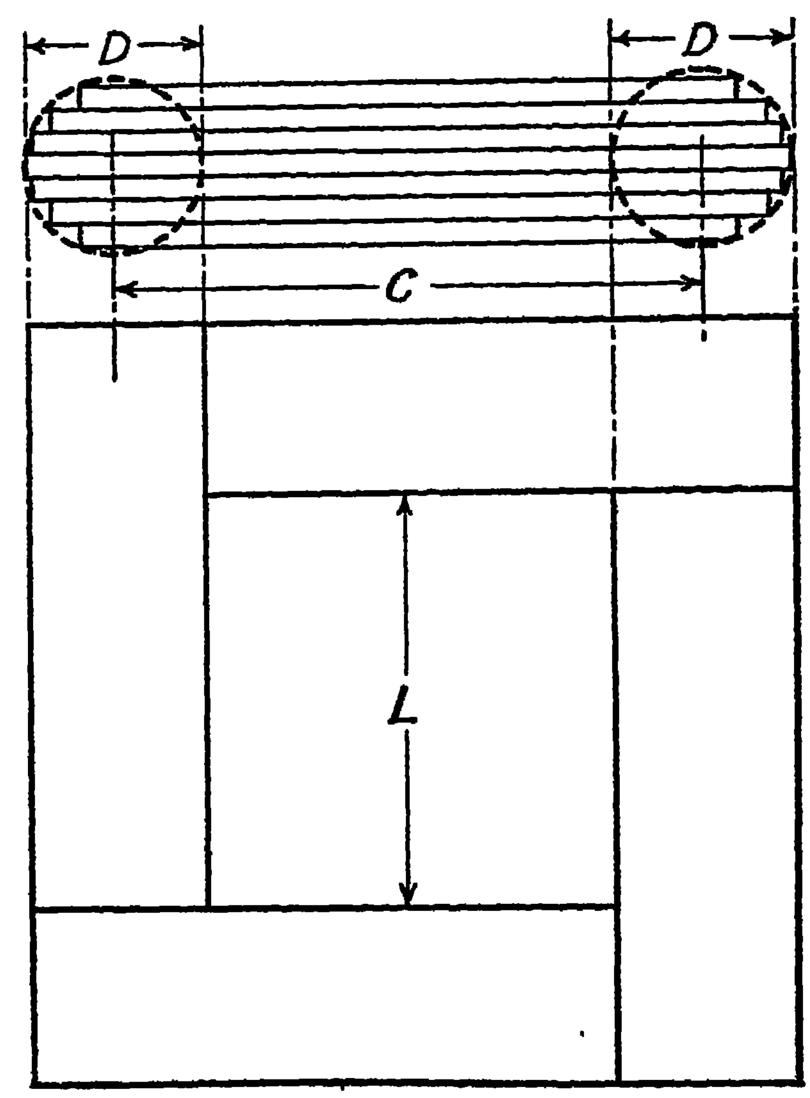



FIG. 167.

The value of C, *i.e.*, the distance between core centres, is largely determined by the voltage that will exist between the ends of the total windings of each limb. From this consideration only it should be as large as possible, but in practice, it is limited by mechanical robustness and the increased energy loss in the "yokes" due merely to the non-useful length of the iron magnetic path. Practice shows a suitable compromise of these two limiting cases to be given by C = 2·5D.

To summarise, we determine our core dimensions from the three empirical equations ;—

$$D = 2{\cdot}25 \times \sqrt[4]{\text{kv.a.}}$$
$$L = 5D \text{ to } 6D$$
$$C = 2{\cdot}5D$$

but it should be mentioned that this is only one empirical method, and nearly every text-book on transformer design gives different methods, all of which lead to approximately the same result.

Having determined these dimensions, the core has to be actually constructed. Whilst soft-iron laminations may be used, invariably

modern transformer cores are of laminated stalloy, the use of which, to prevent eddy currents, has been dealt with in a previous volume. In modern transformers and induction coils these are "stepped" to give an approximately circular cross section, the circle being more closely approached the greater the number of steps.

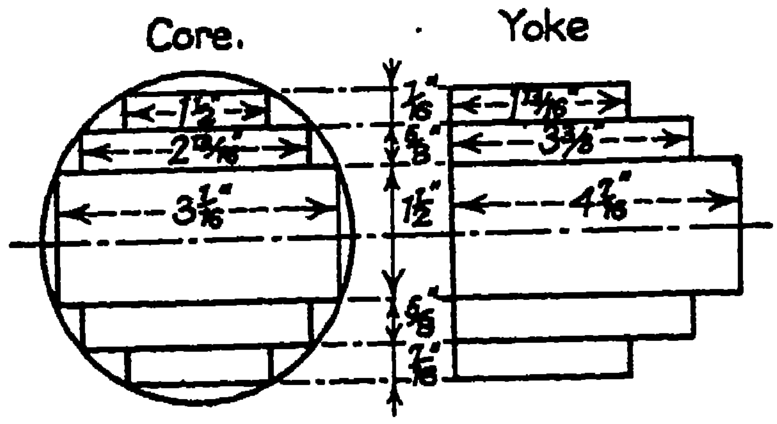


FIG. 168.

Questions of economy in construction reduce the number of steps in practice to three or four, and it is unquestionable that no advantage is obtained by using a great number of steps, since the difference in cross section of the stepped core of a few steps, and the theoretical circular cross section, allows more efficient circulation of oil around the core *viâ* the interstices (Fig. 168), and consequent better cooling. Whilst the iron area is reduced owing to the cross-sectional area of the paper between the laminations, our empirical formula allows for this reduction in actual iron cross section.

These laminations are assembled as in Fig. 169, the relative arrangement of the L-shaped stampings being reversed for each layer, so that alternate laminations overlap and no air gaps, offering large magnetic resistance occur at any corner of the core.

Such resistance effects can be overcome by the use of frame stampings as in Fig. 170.

These however offer considerable winding and insulation difficulties necessitating special methods of manufacture and are usually restricted to low-power high-voltage testing transformers.

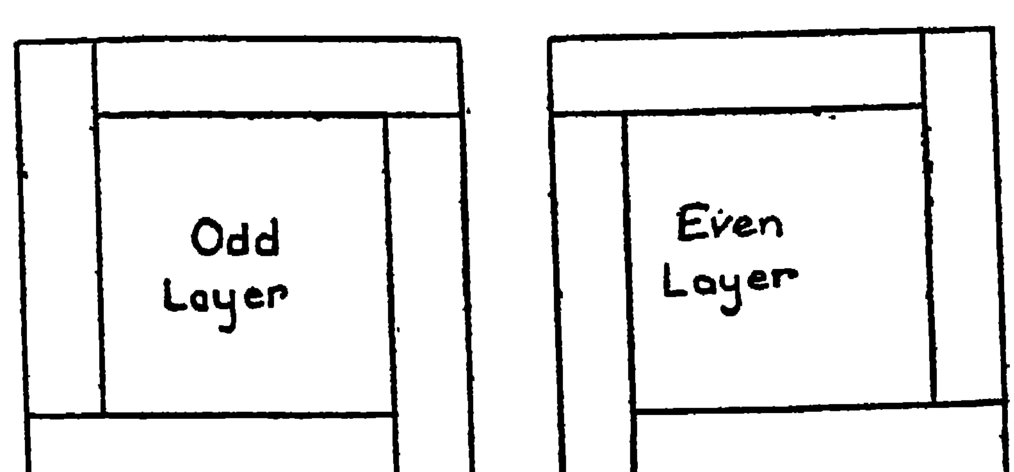


FIG. 169.—Core Laminations.

The subject of magnetic losses has already been dealt with, namely hysteresis and eddy current losses (Chapter III., Vol. I.).

The size of core we have determined would be suitable for transformers working with alternating current of 50 or 60 periodicity, and corresponds to a flux density of about 12,000 magnetic lines per square inch of cross section, *i.e.*, well below the flat portion of the $\frac{B}{H}$ curve (Vol. I.) of stalloy.

For higher frequencies, for example, 500-cycle alternating current as used in the "Radio-Silex" X-ray apparatus, the magnetic medium more

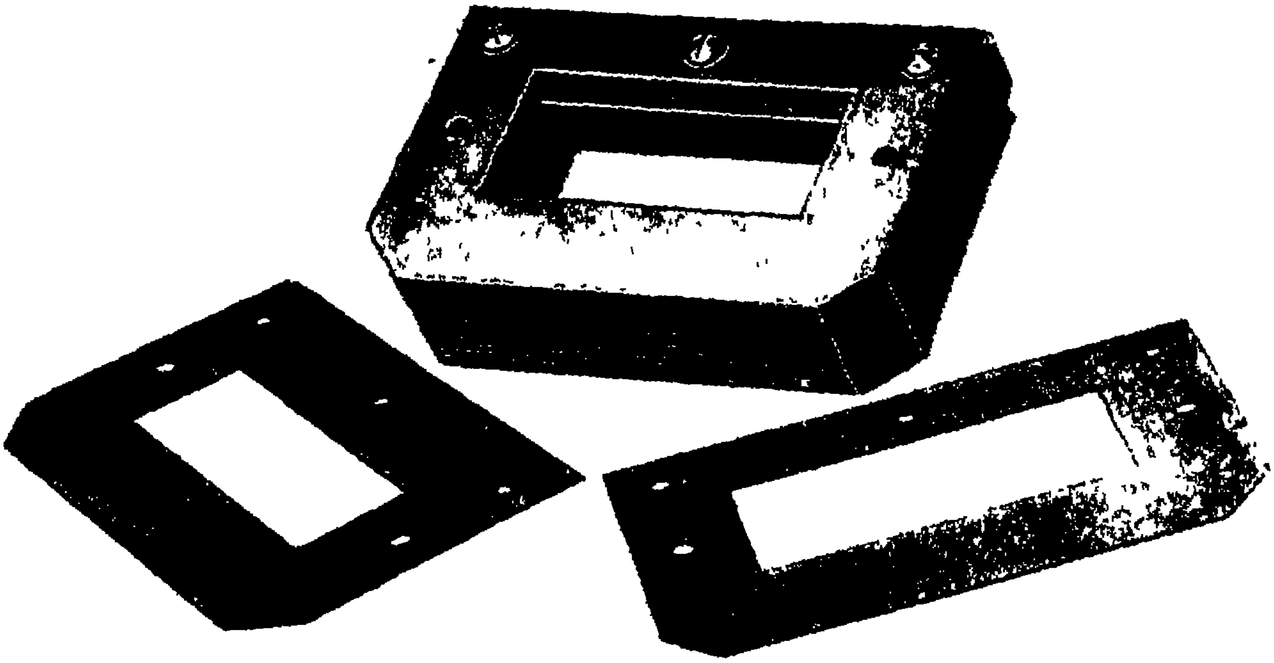


FIG. 170.—Transformer Core Laminations.

[To face p. 208.

the area of the core for 10 kv.a., has already been calculated for a diameter of 4 in., as 9·3 sq. in., after allowing for the paper insulation, and B = 12,000 lines per square inch.

Hence the volts per turn

$$\frac{E}{n} = \frac{1 \times 12{,}000 \times 60 \times 9{\cdot}3}{3{\cdot}49 \times 10^8} = 1{\cdot}594$$

where E = 110 per limb, since the mid-point is earthed.

Hence $$\frac{E}{n} = \frac{110}{n} = 1{\cdot}594 \text{ volts}$$

or $n = 69$ turns per limb for a primary voltage of 220 volts, or $n = 35$ approximately for 110 volts, the mid-point in each case being earthed.

The problem is now to find a suitable wire which will carry as large a magnetising current as possible without overdue heating. This heating will be determined by the total length, over which we have no control, since the core diameter has fixed the length per turn, its specific resistance, which is likewise fixed (copper), its cross-sectional area and the rate at which heat is radiated.

Experience has shown that for any given value of current carried by the wire, under the conditions of radiation obtained with a winding such as that of an oil-cooled winding in a transformer, the permissible density of current per square inch of conductor is 800 to 1,600 amperes. For an X-ray transformer a suitable value would be 1,200 amperes per square inch.

Reference to standard tables drawn up by electrical standards committees shows that a No. 12 standard wire gauge (copper) will safely carry this current, or, if rectangular instead of circular cross-sectional wire is used, as in the best class of transformer, a conductor of area ·2 × ·2 sq. in., the permissible flux density of which is 1,165 amperes per inch.

The advantages of a rectangular wire over a circular wire is that there is a better space economy and, whilst practical difficulties arise in winding rectangular wire, due to the tendency to twist, for a stout wire ·2 × ·2 in. this is not practically important.

Whilst a single ·2 × ·2 in. wire can be used, it is better to use two wires ·2 × ·1 in. in parallel, insulated from each other but connected at the ends, as this allows, if necessary, variation of the primary winding to suit different voltages, for example, such wires may be joined in parallel for 220 volts, or in series, to allow their use upon a 440-volt primary circuit. Also it ensures a more equal distribution of the current and decrease of eddy currents when used in higher frequencies. Further, in the case of interruption of one wire by any cause, as fusing, the primary circuit is not immediately interrupted although the unaffected wire is necessarily then overloaded.

The insulation between turn and turn, in circular wire, need only be a double cotton covering (D.C.C.) or, in the case of rectangular wire, each conductor is covered with a 10-mil cotton covering and the two wires are bound together by 5-mil half-overlapped cotton tape.

Since the voltage between core and primary wire is small (110 volts) there is no need for great insulation between primary and core. A suitable insulation would be to add to the actual wire covering, as above, four layers of 5-mil empire cloth upon which the primary winding would be directly wound, both windings being taped together as above (Fig. 171).

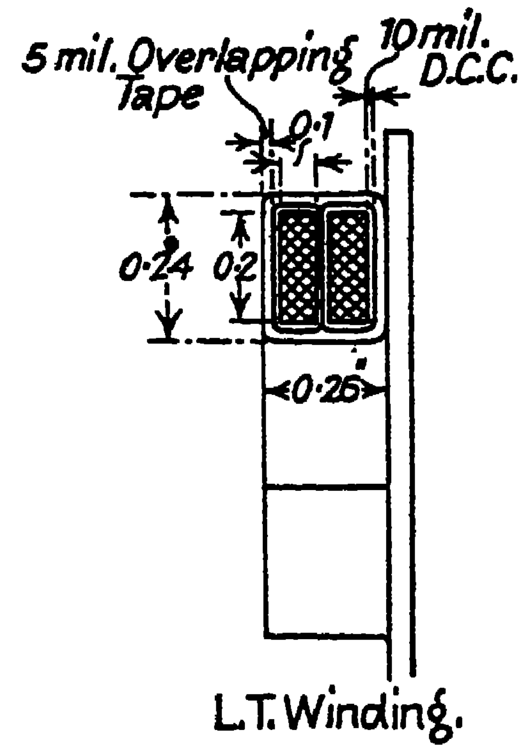



FIG. 171.

As the primary turns of an X-ray transformer do not exceed usually 100 turns (our values being 69 and 35 turns for 220 and 110 volts respectively), there is no need for multiple layer windings as sometimes used in induction coils, and the winding is of the simple layer type.

## THE SECONDARY WINDING

This is determined upon exactly the same considerations as the primary wire and we have ;—

$$\frac{E}{n} = \frac{1}{3{\cdot}49}\,\frac{\beta A \eta}{10^8}$$

and for specific case $\beta = 12{,}000$ lines per square inch, $A = 9{\cdot}3$ sq. in., $n = 60$ cycles ;

$$\frac{E}{n} = 1{\cdot}594,$$

where for a transformer of 250,000 peak volts, or 177,000 volts root mean square value (with earthed mid-point, so that volts per limb $= \frac{177{,}000}{2} = 88{,}500$),

$$n = \frac{88{,}500}{1{\cdot}594} = 55{,}536 \text{ turns,}$$

or for a 125,000 peak volts transformer ; turns per limb $= 27{,}768$ turns, *i.e.*, R.M.S. $125{,}000 = 88{,}500$ and $n = \frac{55{,}536}{2}$.

The gauge of wire is determined, as before, by a limit of 1,200 amperes per square inch, and reference to wire tables shows a No. 36 S.W.G. wire, safely carrying 1,245 amperes per square inch, is suitable.

Owing to the very low current in the secondary circuit of an X-ray

the area of the core for 10 kv.a., has already been calculated for a diameter of 4 in., as 9·3 sq. in., after allowing for the paper insulation, and B = 12,000 lines per square inch.

Hence the volts per turn

$$\frac{E}{n} = \frac{1 \times 12{,}000 \times 60 \times 9{\cdot}3}{3{\cdot}49 \times 10^8} = 1{\cdot}594$$

where E = 110 per limb, since the mid-point is earthed.

Hence $$\frac{E}{n} = \frac{110}{n} = 1{\cdot}594 \text{ volts}$$

or $n = 69$ turns per limb for a primary voltage of 220 volts, or $n = 35$ approximately for 110 volts, the mid-point in each case being earthed.

The problem is now to find a suitable wire which will carry as large a magnetising current as possible without overdue heating. This heating will be determined by the total length, over which we have no control, since the core diameter has fixed the length per turn, its specific resistance, which is likewise fixed (copper), its cross-sectional area and the rate at which heat is radiated.

Experience has shown that for any given value of current carried by the wire, under the conditions of radiation obtained with a winding such as that of an oil-cooled winding in a transformer, the permissible density of current per square inch of conductor is 800 to 1,600 amperes. For an X-ray transformer a suitable value would be 1,200 amperes per square inch.

Reference to standard tables drawn up by electrical standards committees shows that a No. 12 standard wire gauge (copper) will safely carry this current, or, if rectangular instead of circular cross-sectional wire is used, as in the best class of transformer, a conductor of area ·2 × ·2 sq. in., the permissible flux density of which is 1,165 amperes per inch.

The advantages of a rectangular wire over a circular wire is that there is a better space economy and, whilst practical difficulties arise in winding rectangular wire, due to the tendency to twist, for a stout wire ·2 × ·2 in. this is not practically important.

Whilst a single ·2 × ·2 in. wire can be used, it is better to use two wires ·2 × ·1 in. in parallel, insulated from each other but connected at the ends, as this allows, if necessary, variation of the primary winding to suit different voltages, for example, such wires may be joined in parallel for 220 volts, or in series, to allow their use upon a 440-volt primary circuit. Also it ensures a more equal distribution of the current and decrease of eddy currents when used in higher frequencies. Further, in the case of interruption of one wire by any cause, as fusing, the primary circuit is not immediately interrupted although the unaffected wire is necessarily then overloaded.

The insulation between turn and turn, in circular wire, need only be a double cotton covering (D.C.C.) or, in the case of rectangular wire, each conductor is covered with a 10-mil cotton covering and the two wires are bound together by 5-mil half-overlapped cotton tape.

Since the voltage between core and primary wire is small (110 volts) there is no need for great insulation between primary and core. A suitable insulation would be to add to the actual wire covering, as above, four layers of 5-mil empire cloth upon which the primary winding would be directly wound, both windings being taped together as above (Fig. 171).

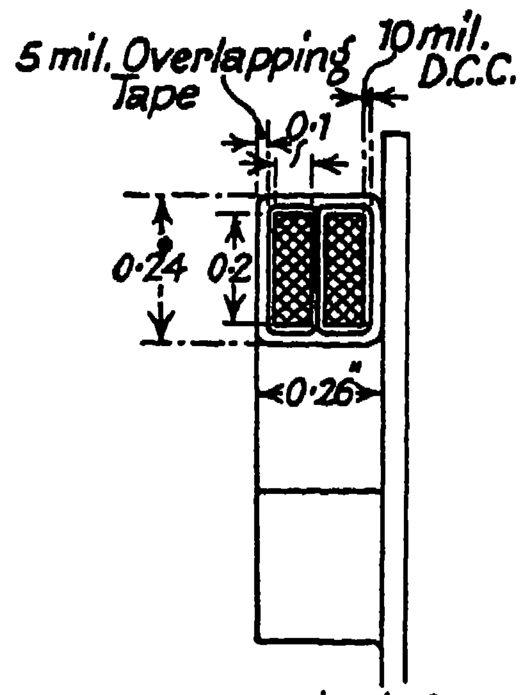



FIG. 171.

As the primary turns of an X-ray transformer do not exceed usually 100 turns (our values being 69 and 35 turns for 220 and 110 volts respectively), there is no need for multiple layer windings as sometimes used in induction coils, and the winding is of the simple layer type.

## THE SECONDARY WINDING

This is determined upon exactly the same considerations as the primary wire and we have ;—

$$\frac{E}{n} = \frac{1}{3{\cdot}49}\,\frac{\beta A \eta}{10^8}$$

and for specific case $\beta = 12{,}000$ lines per square inch, $A = 9{\cdot}3$ sq. in., $n = 60$ cycles ;

$$\frac{E}{n} = 1{\cdot}594,$$

where for a transformer of 250,000 peak volts, or 177,000 volts root mean square value (with earthed mid-point, so that volts per limb $= \frac{177{,}000}{2} = 88{,}500$),

$$n = \frac{88{,}500}{1{\cdot}594} = 55{,}536 \text{ turns,}$$

or for a 125,000 peak volts transformer ; turns per limb $= 27{,}768$ turns, *i.e.*, R.M.S. $125{,}000 = 88{,}500$ and $n = \frac{55{,}536}{2}$.

The gauge of wire is determined, as before, by a limit of 1,200 amperes per square inch, and reference to wire tables shows a No. 36 S.W.G. wire, safely carrying 1,245 amperes per square inch, is suitable.

Owing to the very low current in the secondary circuit of an X-ray

transformer and consequent small heating effect, as the heat is proportional to the square of current, a much higher flux density would be permissible. Practice shows however that it is more economical to employ a wire not less than No. 36 S.W.G., otherwise the wire is so thin that the risk of fracture in winding and difficulty of manipulation, is very great. Also a thicker wire means smaller heat losses with decreased rise of temperature, and local "hot-spots" in a closely wound winding are not so likely to occur.

A smaller gauge than No. 36 S.W.G., *i.e.*, No. 32 of greater cross section, will naturally decrease the resistance and heat formation to about one-quarter that of No. 36, with greater secondary output, still less risk of hot-spots, and easier manipulation during winding, but with greater space consumption, so that the outer layers are more distant from the strong magnetic field of the core. As however the current obtained with a No. 36 wire will already be more than the modern X-ray tube can safely carry, the use of a stouter wire is not of great advantage, unless it is proposed to permit the simultaneous running of several X-ray tubes, as in some German X-ray installations.

It must also be recollected that, as energy is drawn off from the secondary circuit of a transformer, so more energy flows into the primary circuit from the mains and, if a large secondary current is to be taken, the size and insulation of the primary circuit must be correspondingly modified. In turn, the effective cooling oil volume surface of the tank, etc., must be modified to radiate the greater heat energy produced. On the other hand a large secondary current largely compensates for the decrease of current when high-resistance X-ray tubes are used. Since the voltage drop across the tube may be roughly considered as of value $E = CR$, an increase of total resistance of the circuit is partially compensated for by a decrease in current, with less effect upon the total voltage, *i.e.*, where a hard tube might reduce a current of 10 milliamperes to 5 amperes, it is of advantage to have a transformer of large current-carrying capacity, so that this current may be safely increased to 20 milliamperes, to still give 10 milliamperes current with a hard tube in circuit.

The arrangement of the secondary circuit is largely a matter of individual taste. As in the induction coil (*q.v.*), a sectional winding is usually utilised, and the guiding factors are ;—

(1) Transformer practice puts a limit of 5,000 volts per section, which in the case of X-ray low-current transformers may be increased to 6,000 to 7,000, a limiting value invariably greatly exceeded by X-ray apparatus manufacturers.

(2) The depth of coil should be small (within 1·5 in.) to facilitate heat conduction from the centre of the coil, a further transformer design requirement invariably exceeded by the X-ray manufacturer.

Both these requirements are often not observed, and may be considered as the prime cause of the frequent breakdowns in X-ray work, as compared to other branches of transformer operation. It is quite common and the rule, rather than the exception, for a 120,000-volt transformer to be wound directly with 30,000 turns per limb, with consequent risk of flash over between adjacent turns, particularly since the cheapest form of insulation (oil-paper) is often used.

In one particular case a 125,000-volt X-ray transformer is wound in

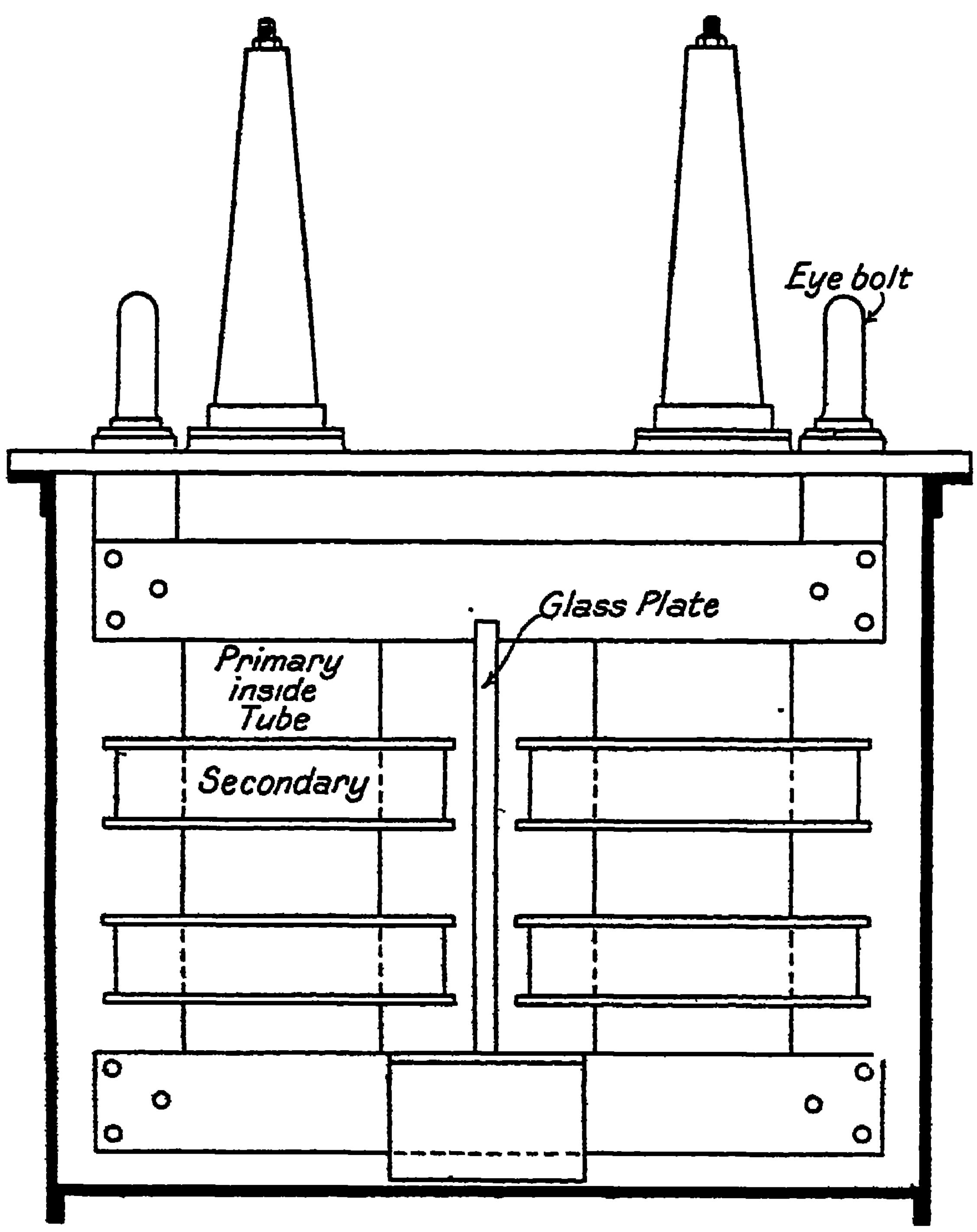



FIG. 172.

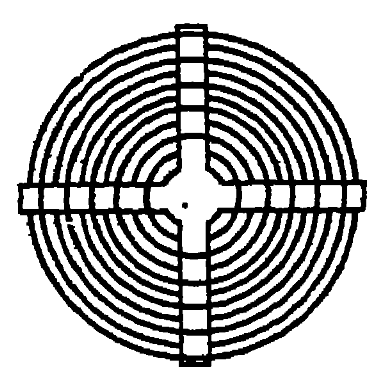


FIG. 173.—Coil Spider.

two sections per limb, between oiled paper of 2 in. width, leaving about ½ in. of paper on each side unwound, *i.e.*, the winding is 1 in. wide. The four coils of 15,000 turns are then arranged as Fig. 172, by means of spiders of the form shown in Fig. 173, these serving to hold the two paper coils apart. Such a form is mechanically wrong, since it can be shown that, on making or breaking the current, considerable mechanical force is thrown upon the windings, which tends to move the windings transversely, *i.e.*, in the direction of the core length.

This force may be calculated mathematically as ;—

$$F = \frac{BIl}{10}$$

transformer and consequent small heating effect, as the heat is proportional to the square of current, a much higher flux density would be permissible. Practice shows however that it is more economical to employ a wire not less than No. 36 S.W.G., otherwise the wire is so thin that the risk of fracture in winding and difficulty of manipulation, is very great. Also a thicker wire means smaller heat losses with decreased rise of temperature, and local "hot-spots" in a closely wound winding are not so likely to occur.

A smaller gauge than No. 36 S.W.G., *i.e.*, No. 32 of greater cross section, will naturally decrease the resistance and heat formation to about one-quarter that of No. 36, with greater secondary output, still less risk of hot-spots, and easier manipulation during winding, but with greater space consumption, so that the outer layers are more distant from the strong magnetic field of the core. As however the current obtained with a No. 36 wire will already be more than the modern X-ray tube can safely carry, the use of a stouter wire is not of great advantage, unless it is proposed to permit the simultaneous running of several X-ray tubes, as in some German X-ray installations.

It must also be recollected that, as energy is drawn off from the secondary circuit of a transformer, so more energy flows into the primary circuit from the mains and, if a large secondary current is to be taken, the size and insulation of the primary circuit must be correspondingly modified. In turn, the effective cooling oil volume surface of the tank, etc., must be modified to radiate the greater heat energy produced. On the other hand a large secondary current largely compensates for the decrease of current when high-resistance X-ray tubes are used. Since the voltage drop across the tube may be roughly considered as of value $E = CR$, an increase of total resistance of the circuit is partially compensated for by a decrease in current, with less effect upon the total voltage, *i.e.*, where a hard tube might reduce a current of 10 milliamperes to 5 amperes, it is of advantage to have a transformer of large current-carrying capacity, so that this current may be safely increased to 20 milliamperes, to still give 10 milliamperes current with a hard tube in circuit.

The arrangement of the secondary circuit is largely a matter of individual taste. As in the induction coil (*q.v.*), a sectional winding is usually utilised, and the guiding factors are ;—

(1) Transformer practice puts a limit of 5,000 volts per section, which in the case of X-ray low-current transformers may be increased to 6,000 to 7,000, a limiting value invariably greatly exceeded by X-ray apparatus manufacturers.

(2) The depth of coil should be small (within 1·5 in.) to facilitate heat conduction from the centre of the coil, a further transformer design requirement invariably exceeded by the X-ray manufacturer.

Both these requirements are often not observed, and may be considered as the prime cause of the frequent breakdowns in X-ray work, as compared to other branches of transformer operation. It is quite common and the rule, rather than the exception, for a 120,000-volt transformer to be wound directly with 30,000 turns per limb, with consequent risk of flash over between adjacent turns, particularly since the cheapest form of insulation (oil-paper) is often used.

In one particular case a 125,000-volt X-ray transformer is wound in

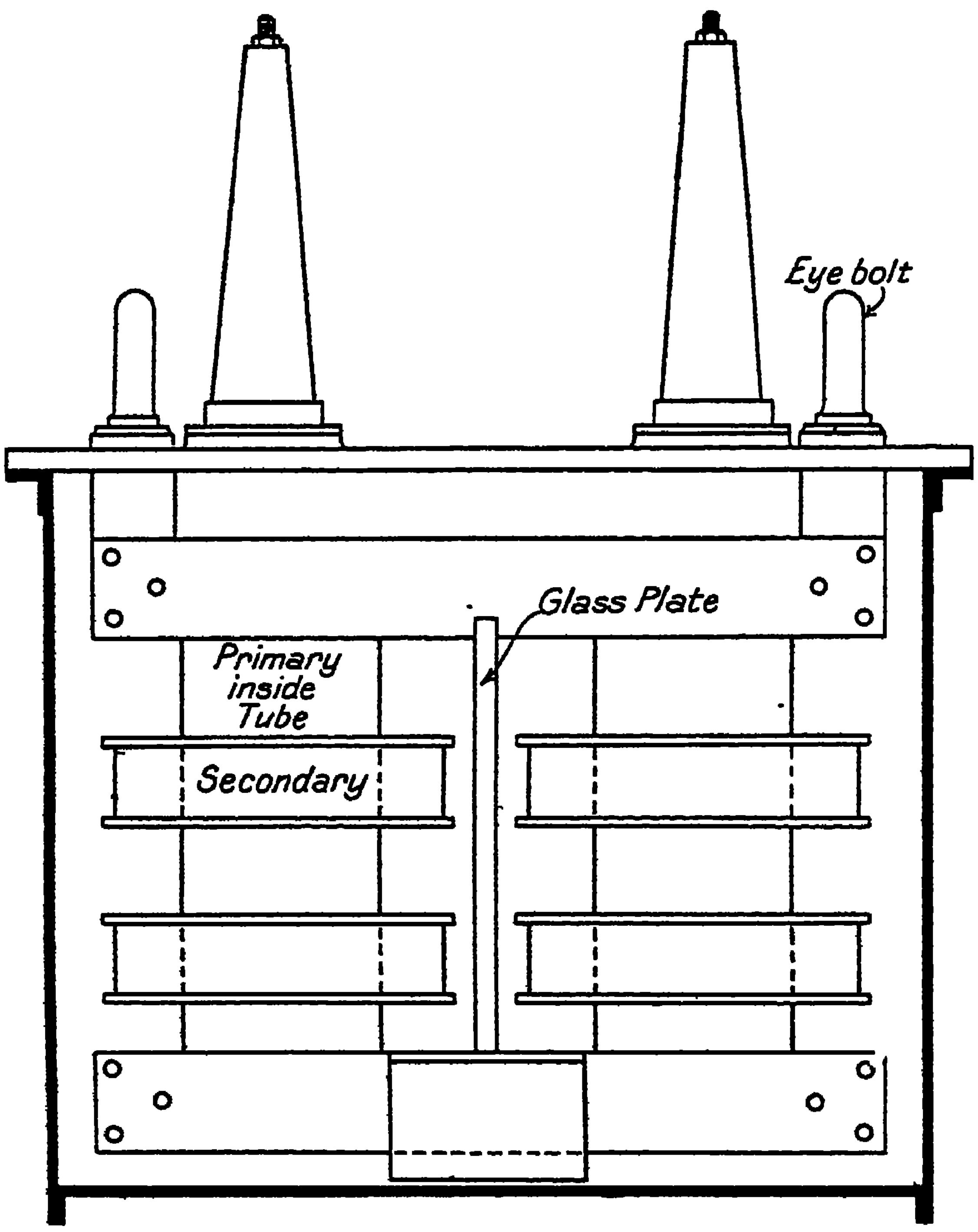



FIG. 172.

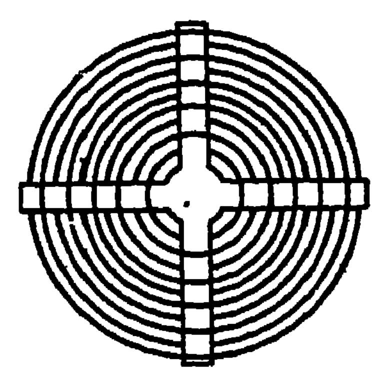


FIG. 173.—Coil Spider.

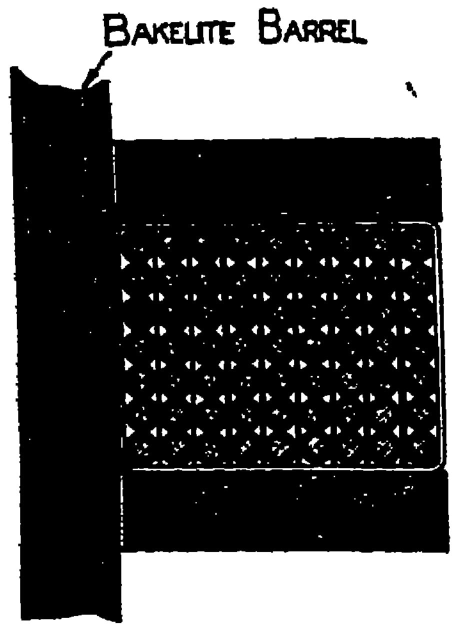
two sections per limb, between oiled paper of 2 in. width, leaving about ½ in. of paper on each side unwound, *i.e.*, the winding is 1 in. wide. The four coils of 15,000 turns are then arranged as Fig. 172, by means of spiders of the form shown in Fig. 173, these serving to hold the two paper coils apart. Such a form is mechanically wrong, since it can be shown that, on making or breaking the current, considerable mechanical force is thrown upon the windings, which tends to move the windings transversely, *i.e.*, in the direction of the core length.

This force may be calculated mathematically as ;—

$$F = \frac{BIl}{10}$$

this book, and those further interested should consult text-books of transformer practice and manufacture.

This impregnating and baking process is the one usually followed. On the other hand some competent electrical machinery makers contend this baking process, particularly if pushed too far, destroys the insulating properties, owing to acids being produced by breakdown of the varnish. It is claimed * that the older electrical machinery, constructed before baking came into vogue, has in practice withstood more severe work than the more modern highly impregnated and baked insulation. For this reason some X-ray manufacturers omit this impregnating and baking process. For example, Messrs. X-rays, Ltd., claim they have proved by test, that, with the most intensive vacuum-exhaustion, impregnation and baking, a section of the coil shows the absence of impregnating material at the centre of the coil. For this reason they rely on a different method of winding in which, just prior to actual winding, the wire is passed through hot oil, in much the same manner as the wire passes *viâ* melted paraffin wax in induction-coil manufacture.




ENLARGED VIEW OF I H.T. COIL.

FIG. 174.

The heat drives off any air or moisture and the wire receives a coating of hot oil, which is held to the wire by surface tension. So, as the wire is wound, the only medium between turn and turn is oil, any air being expressed as the coil is wound turn by turn and layer by layer. After assembly the coils are further heated in the oil in the transformer tank for some hours, but only to a moderate degree.

When the coils by the usual method are varnish impregnated, they are given a final baking after the coils are assembled upon the core and primary. To increase the insulation distances between coil and coil, they are separated on the core by a layer of insulating material, such as fullerboard, or washers of such material, placed between the coils to hold them apart and so to allow oil to flow between coil and coil, for cooling purposes.

The coils are finally rigidly braced together, by building up the end clearances with washers of insulating material, varying from circular discs of fullerboard to more expensive insulation, as paxolin. Such a method is seen in Fig. 175.

*Losses in the Windings.*—These losses consist of ;

(1) Ohmic resistance losses.
(2) Eddy current losses.
(3) Magnetising current losses.
(4) " Skin effect " losses at high frequencies.

* Bartlett, *I.E.E. Journal*, p. 80, Vol. 52, 1914.

Of these losses the most important is the ohmic resistance loss. It is usual to multiply by an empirical formula, derived from direct tests, to allow for the eddy current losses. The eddy currents are due to currents flowing transversely in the conductor, owing to those portions of the conductor nearer to the axis of the core being in a more intense field than those more distant and having, as a result, a different potential induced in them as the magnetic field varies (see p. 98, Vol. I.). For thin wires the eddy current loss is usually small at low frequencies and similarly the "skin effect" resistance (p. 147, Vol. I.) is likewise negligible at low frequencies.

The magnetising current loss represents the energy lost by hysteresis effects, *i.e.*, energy of the magnetic field, established by the current

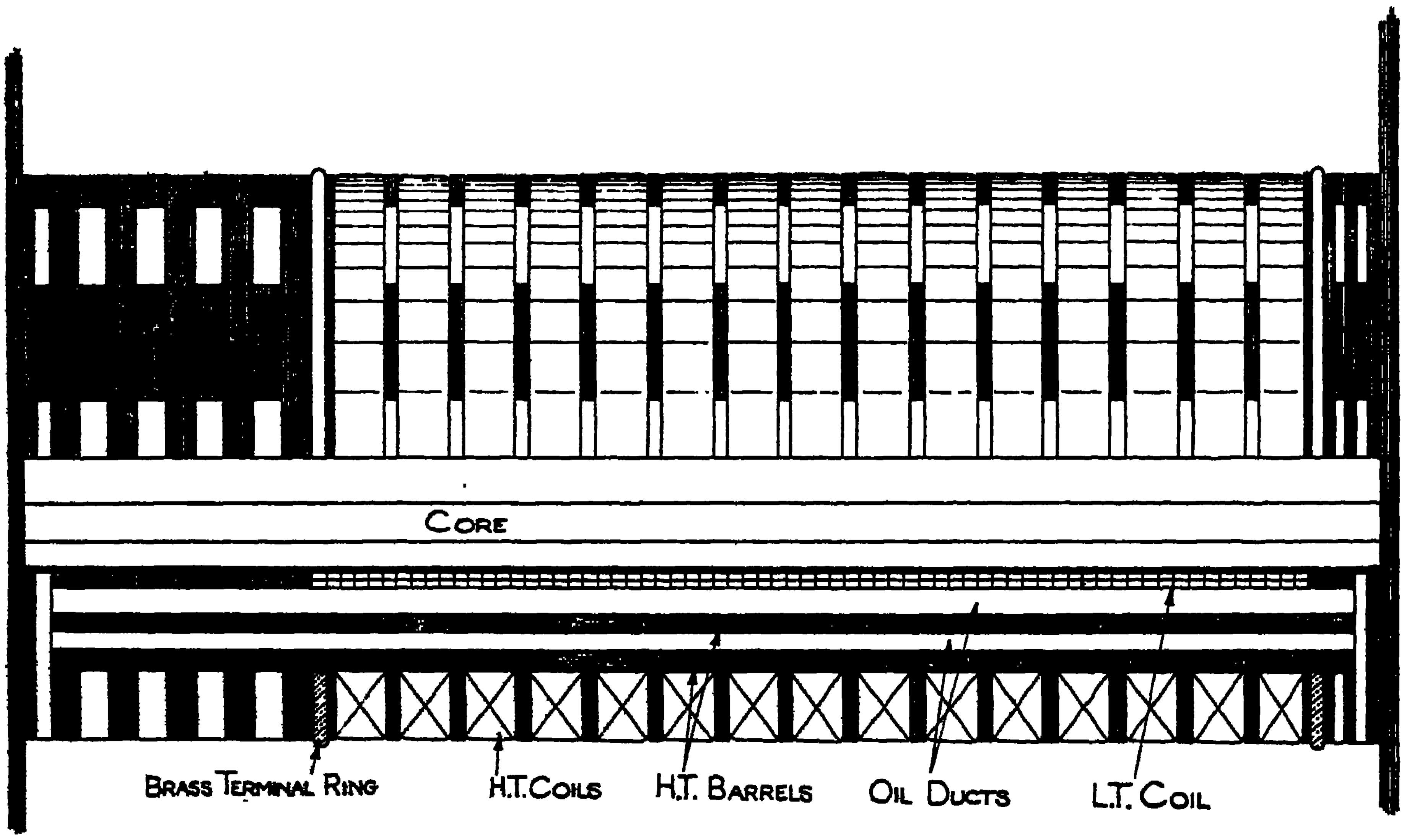



FIG. 175.—Section of Limb of 225-kv. Transformer.

flow, is not entirely given back to the conductor, as the field reverses with the change of current direction (see Chapter III., Vol. I.).

The most important loss is the ohmic resistance loss, which we can easily predetermine, the calculation consisting of finding the whole length of turn per primary and secondary conductor and, knowing the cross-sectional area and consequent specific resistance, so determining the total resistance. Such values, actually determined for steady current values, differ but little from alternating current values at low frequencies, as 60 cycles.

For example, in our given case we have for the primary ;—

| | | |
|---|---|---|
| Length of mean turn | = | 13·9 in. |
| Total length ($l$) | = | 1,920 in. |
| Cross-sectional area (A) | = | ·039 sq. in. |

Total resistance $= \frac{\rho l}{A} = \frac{\cdot 668}{10^6} \times \frac{1920}{\cdot 039} = \cdot 033\omega$;

where $\rho = \frac{\cdot 668}{10^6}$

$I^2R$ watts loss $= (45\cdot 5)^2 \times \cdot 033$
$= 68\cdot 3$ watts.

Similarly for the secondary winding consisting of No. 17 S.W.G.;

Length per mean turn $= 26\cdot 2$ in.
Total length of No. 17 S.W.G ($l$) $= 13{,}700$ in.
Cross-sectional area of No. 17 (A) $= \cdot 00246$ sq. in.
Total resistance $= \frac{\rho l}{A} = \frac{\cdot 668}{10^6} \times \frac{13{,}700}{\cdot 00246}$
$= \cdot 373\omega$.

Since the resistance is very low and also the current (milliamperes), the ohmic loss is negligible.

For the coils of the secondary circuit wound with No. 36 S.W.G., the resistance is high and this loss is of importance, and we have;—

Total length $= 2{,}900{,}000$ in. ($45\cdot 75$ *miles*)
Cross-sectional area $= \cdot 0000454$ sq. in.
Total resistance $= \frac{\rho l}{A} = \frac{\cdot 168}{10^6} \times \frac{2{,}900{,}000}{\cdot 0000454}$
$= 42{,}800\ \omega$
$I^2R$ loss $= \cdot 565^2 \times 42{,}800 = 137$ watts.

Allowing 10 per cent. increase for eddy current loss, etc. (50 cycles), the total copper loss is 226 watts at normal temperature (15·5° C.). Since during continued operation the external temperature may permissibly vary to 25° C. and the winding temperature attain 50° C., the total losses, at 50° C., would be:

| | |
|---|---|
| $I^2R$ losses | 234 watts. |
| Copper eddy losses | 18 ,, |
| Total | 252 watts. |

It is this total loss, known as the "copper loss," plus the magnetic "iron losses," which is used to calculate the approximate temperature rise of the oil (see p. 233) to determine the size of tank to give efficient cooling.

In the case of a 500-cycle transformer, the calculation is more involved, and the eddy current and skin-effect losses become proportionally much greater. These losses may be calculated, but the formulæ are considerably involved (see "Skin Effect," Vol. I.). In practice such losses would be largely neutralised by selection of a wire of greater periphery, to lower the value of the skin resistance, for example No. 32 S.W.G., or by using multiple wires say, two of No. 40 S.W.G. Also in practice the skin losses

would be determined directly, by, for example, the balance method described (p. 147, Vol. I.) for a given length of wire at this particular frequency, and the value so obtained used in a calculation much as above.

## THE DIELECTRIC CIRCUIT

Of utmost importance, in the design of insulation for high-tension transformers, are the conceptions of concentration of electrostatic flux and resultant breakdown, and the length of the leakage path, which have been sufficiently developed in Chapter I., Vol. I.

It is customary to consider the various regions of insulation in a transformer as *major insulation* and *minor insulation*. This is an arbitrary conception based roughly upon the relative thicknesses of insulation employed. It should be appreciated, as breakdown of the transformer will result by breakdown of either major or minor insulation, the latter is equally as important as the former, or even, since minor insulation is that between winding and winding, whereas major insulation is that between primary and secondary, actually the repair of minor insulation, necessitating rewinding, may be a more lengthy and more costly process than the more easy replacement of major insulation.

The division of the various regions of insulation into major and minor is as follows ;—

*Major.*

(1) Between high-tension and low-tension windings.
(2) Between low-tension windings and core.
(3) Between adjacent limbs.
(4) Between high-tension windings and yokes.

*Minor.*

(5) Between adjacent turns in any one layer of winding.
(6) Between adjacent layers of windings.
(7) Between adjacent sectional coils.

These will be considered in turn.

(1) *Between High-tension and Low-tension Windings.*—This consists of one or more insulating sleeves with corresponding oil ducts. These cylinders are usually ebonite, varnished paper (paxolin, etc.), micanite, etc.,

The total thickness of insulation may be taken as $\frac{1}{8}$ in. for every 20,000 volts *test* pressure, and the oil ducts and solid insulation must be correctly proportioned.

The ratio of calculated ultimate breakdown and test pressure should not be less than 2, and, for smaller lower tension transformers, can be advantageously a much higher ratio, and is necessarily so since, owing to reasons of mechanical strength, the solid insulation has minimum values of $\frac{1}{8}$ in. and, owing to the danger of dirt accumulating between the solid insulation, the ducts have usually minimum values of $\frac{1}{4}$ in.

The importance of the correct proportioning of solid and liquid dielectrics will be made evident as follows ;—

Let the insulation between the primary and secondary of an oil immersed transformer consist of two ·8-cm. paxolin tubes, separated by an oil space of ·8 cm. (Fig. 176) and let the difference between primary and secondary windings be 250,000 volts. If we consider such a combination from the more usual aspect of capacity, we shall find the capacity between primary and secondary windings to be enormous. If however we consider the problem from the aspect of electrostatic flux, we shall find that whereas 1·6 cm. of paxolin should withstand a voltage of at least 500 kv., in practice the introduction of further insulating oil will practically cause breakdown.

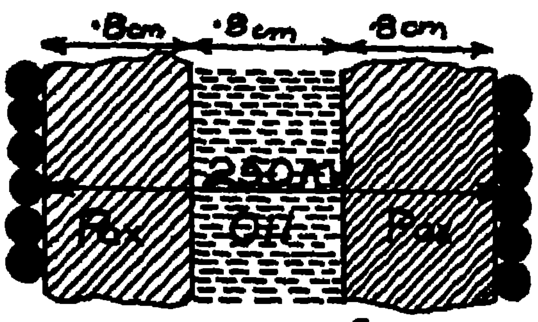


Fig. 176.

Let the specific inductive capacity of oil and paxolin be 2 and 5 respectively. As in the case of the composite air and glass condenser (Chapter I., Vol. I.), let the permissible potential gradient in oil and paxolin be $G_{oil}$ and $G_{pax.}$ respectively, then for the values of specific inductive capacities of 2 and 5 we may write ;—

$$2\ G_{oil} = 5\ G_{pax.}$$

The potential slope is, as in Vol. I.,

$$\begin{aligned} 250{,}000 &= \cdot 8\ G_{oil} + 2 \times \cdot 8\ G_{pax.} \\ &= (\cdot 8 \times 2\cdot 5 + 2 \times \cdot 8)\ G_{pax.} \\ &\qquad \text{since } G_{oil} = 2\cdot 5\ G_{pax.} \end{aligned}$$

from which ;—

$$G_{pax.} = \frac{250{,}000}{3\cdot 6} = 70{,}000 \text{ volts/cm.}$$

$$\text{and } G_{oil} = 172{,}000 \text{ volts/cm.}$$

Since transformer oil is specified to only withstand 40,000 volts between a ·15-in. spark gap, or 105,000 volts/cm., the oil will be unduly stressed. As this will then decompose and form conductive carbon deposits, no beneficial, but a harmful, effect has been obtained by increasing the insulation by means of oil, and the construction will consequently need modification.

In practice this will require the oil gap to be at least 2·5 times the thickness of the solid paxolin insulation, *i.e.*, 4 cm. and, if we are to retain the two tubes, the oil gap and solid insulation must be proportioned inversely as the specific inductive capacities, with a factor of safety in favour of the weakest dielectric, *i.e.*, 5 cm. of oil would be allowed.

This increase of oil thickness would naturally increase all winding dimensions and corresponding copper losses. Whilst practicable it is undesirable.

Practically the difficulty is overcome by earthing the mid-point of the secondary winding, in which case, for each limb, we may write ;—

$$\frac{250{,}000}{2} = 125{,}000 = \cdot 8\ G_{oil} + 2 \times \cdot 8\ G_{pax.}$$

$$\text{whence } G_{pax.} = 30{,}000 \text{ volts/cm.}$$
$$G_{oil} = 84{,}000 \text{ volts/cm.}$$

Now the oil stress is well below the test stress of 105,000 volts/cm., and, as it is capable of continuous circulation by convection currents, it will not be unduly stressed.

As already mentioned, minimum distances of oil and solid insulation are $\frac{1}{4}$ in. and $\frac{1}{8}$ in. respectively to prevent blocking of oil ducts and mechanical fragility of solid insulation.

The above reasoning will show the unsuitability of glass for the insulation between primary and secondary, as here we have to deal with specific inductive capacities which may differ by as much as 5 to 1, since the specific inductive capacity of glass may vary from 7 to 10, as compared with oil of value 2. In the given case if paxolin is replaced by ·8-cm. thick glass the oil distance would need to be at least 8 cm.

Considerations as above will show that, for a 250,000-volt mid-point earthed transformer, suitable insulation will be two bakelite or paxolin cylinders each $\frac{5}{16}$ in. thick and having diameters as follows ;—

$5\frac{1}{4}$ in. inside and $5\frac{7}{8}$ outside
$6\frac{1}{2}$ „ „ and $7\frac{1}{8}$ „

allowing a $\frac{5}{16}$ in. oil duct between the cylinders.

For a 125,000-volt instrument with earthed mid-point suitable insulation would be a single $\frac{3}{8}$-in. thick paxolin tube, or better two $\frac{1}{4}$-in. tubes with a $\frac{3}{16}$-in. oil duct, or even better (when $\frac{3}{16}$-in. paxolin tubes are obtainable and can be worked) two $\frac{3}{16}$-in. tubes with at least $\frac{1}{8}$-in. oil duct and, better, $\frac{3}{16}$-in, oil duct.

In the latter case the solid dielectric thickness will be that of a single $\frac{3}{8}$-in. thick tube. The use of two tubes of half this thickness, with a suitable oil duct, is preferable, as with the insulation so divided the risk of a flaw extending all through the thickness of solid dielectric is practically nil in the case of two separate tubes, but quite possible in the case of a single tube. The division also allows the presence of oil between the total thickness of solid insulation, so that heat, due to electrostatic hysteresis, is more efficiently removed than in the case of a single thick tube.

(2) *Low-tension Windings and Core.*—As the voltages coming into consideration here are small (100 to 500 volts) this is simply one or more layers of flexible presspahn or Empire cloth, on which the primary wire, already insulated by its covering (see p. 213), is wound direct (Fig. 177).

The factor of safety is therefore exceedingly high unless the primary

enamel is liable to be dissolved off by the spirit in the shellac, if the wire is shellacked layer after layer. The author has found this not to occur even with a long immersion in methylated spirit and, in practice, when so coated, the spirit is less concentrated and only effective during the short period of drying.

Cotton-covered wire is very little dearer than enamel wire and, whilst not liable to destruction by cracking as enamel wire, it is, to the author's mind, distinctly likely to retain air, later giving rise to brush discharge, even when impregnated with hot oil before winding.

Silk-covered wire is more expensive than the above wires, and whilst withstanding a greater voltage pressure, to the author's mind suffers from the same disadvantage as cotton covering, whilst both have the advantage of the thicker covering, so that spacing of the turns is facilitated.

The circuit formed by the X-ray tube and secondary circuit contains both inductance and capacity and may, in consequence, give rise to high-frequency oscillations or surges. Such surges may give rise at the ends of the secondary winding of the transformer to potential differences forty or fifty times that of the actual volts per turn. Moreover, such high-frequency surges pass between neighbouring portions of the secondary winding more easily, by electrostatic induction across intervening insulation, than as a conductive current *viâ* the highly inductive winding. As a result there is a very great tendency for such surges to break down the insulation at the ends of the secondary winding. To prevent such breakdown of insulation, it is necessary to reinforce the insulation of the ends of the secondary winding. This is done by taping each individual wire with one or more turns of insulating material, as cotton tape, or, better, Empire cloth, which, to prevent possible breakdown due to flaws of the cloth or tape, should be composed of two or more overlapping layers. Since a fine-gauge wire as No. 36 S.W.G. does not lend itself to such reinforcement in view of its fragility, a stouter wire, as No. 17 or No. 18 S.W.G., is mostly used for the last secondary turns.

For a 250,000-volt transformer two layers of half-overlapping tape, or, better, two layers of half-overlapping 5-mil Empire cloth, would be suitable. In such a case, neglecting the additional insulation of the wire covering itself, 10 mils thickness of Empire cloth would safely withstand approximately 5,000 volts but, as in the case of all insulation, the real criterion is the absence of flaws in the insulation, and that the insulation does not deteriorate rapidly, if worked at a higher temperature than the normal working temperature.

(6) *Between Layer and Layer.*—This insulation depends very largely upon the turns per layer, and, taking our specific example of eighty-four turns per layer, the induced voltage per layer is $84 \times 1{\cdot}594 = 134$ and therefore, between ends of adjacent layers, 278 volts. Probably the insulation of the wire alone would be sufficient to withstand easily this

voltage but, since surges may occur, a large factor of safety must be allowed. The insulation between layer and layer is therefore reinforced by flexible 10-mil oil-impregnated Manilla paper, or, better, if the question of cost does not operate, with 10-mil Empire cloth, which is not so liable to deteriorate with time and has a greater dielectric value. As usual, to avoid the effect of flaws, this 10-mil thickness is best made of two or more layers, rather than a single layer. For the end coils, which have to withstand high-frequency surges, Empire cloth is alone permissible, even although these turns have been previously taped. The layers of insulation should extend at least ½ in. beyond the winding, in order to avoid creepage and flashing over between the end turns of the layers.

(7) *Between Adjacent Coils.*—The voltage per coil rarely exceeds 7,000-volts, and most designers specify a limit of 5,000-volts. A single cheek of insulating material of about ¼ in. will be sufficient to withstand this pressure. This may be of fullerboard, or, better, if expense is not to be considered, ebonite or paxolin. This cheek should be continued radially at least 1 in. beyond the the winding to prevent creepage.

Even better is the spacing of the coils one from the other, in order to allow oil to circulate between them and so to cool the windings as well as to increase the creepage distance. Since the total voltage difference is only 5,000 volts, the relative thickness of the oil layer between the cheeks does not come into question in this case, since this thickness must, for mechanical reasons, be at least ⅛ in. Should ebonite be used for the cheeks, this should be a matt-surface and not a polished surface, as such a polished surface is usually conductive, owing to its containing conductive polishing material.

*Additional Protection against High-frequency Surges.*—We have seen that in a correctly designed transformer the windings are so arranged to prevent and to reduce the occurrence of large potential differences between adjacent parts but that, in spite of this, insulation has to be calculated at a very high factor of safety on account of high-frequency surges produced by the secondary circuit acting as an inductive-capacity, or oscillatory discharge circuit. Such high-frequency disturbances may be divided into three groups :—

(1) Impulses, which are sudden waves of voltage or current, and are not oscillatory and produced by switching operations, as throwing an X-ray tube in or out of circuit.

(2) Oscillations, which are gradually damped out by the circuit resistance.

(3) Cumulative oscillations or surges, which, acting in resonance with a portion of the circuit, increase in amplitude until destruction of the circuit occurs, or they are finally limited by increasing energy losses.

It has been already explained (p. 150, Vol. I.), that with such high-frequency surges, having a very great frequency of oscillation, that owing to

(p. 194, Vol. I.). Whilst often used upon wireless transformer circuits, operating at moderately high voltages (as expressed in high-voltage terms), they are rarely if ever used in the higher voltage transformers of X-ray practice, although the development of high-voltage transmission systems abroad is making their advantages more evident. Their objection in such cases is the practical difficulty of designing a condenser of moderate size capable of withstanding the high voltages involved, the insulation of which is complicated by the necessity of considering lower dielectric values in reference to the high-frequency surges.

## THE HIGH-TENSION INSULATORS

Although the design of a high-tension insulator appears at first sight simple, in actuality the design is a very specialised branch of electrical engineering. In addition to the study of the dielectric properties of the insulating material, usually porcelain, and, less frequently, glass or paxolin, the actual geometrical form is of importance, in order that there should be no localised electrostatic stressing of the neighbouring air, which would result is ionisation, brush discharge and surface conduction.

Many of the very high-voltage transformers have actually been specifically produced for the purpose of testing the insulating properties of such insulators, designed for use in high-voltage transmission systems.

As such high-voltage transmission systems are not, up to the present, employed in England, the study of such insulators has not been greatly developed in England and practically all of the insulators, for voltages above 125,000, are of foreign origin.

The chief requirements of high-tension insulators are ;—

(1) Ability to withstand the high electrical pressure involved.

(2) Avoidance of " creepage," by allowing a sufficiently great surface.

(3) Avoidance of concentration of electrostatic flux at any point which, by causing the air to be ionised, would result in passage of current.

The first requirement is dependent upon the insulating material. The dielectric strength of good porcelain is about 110 kv. per centimetre, so that, for a 250-kv. transformer, we require at least 1 in. thickness (2·54 cm.) if the mid-point is earthed, in order to allow a factor of safety of 2·5, or, still better, of thickness of 1·5 in. As the conductor is at the centre of the insulator, this requires a total diameter of 3 in. of porcelain, without the addition of the diameter of the tubular conductor. As merely to insert such a tubular conductor within the porcelain cylinder would produce a small air gap between conductor and porcelain, which would be overstressed and ionised, the conductor must be cemented in by some insulating cement, and the total diameter is therefore increased to possibly 4 in.

Creepage of energy over the surface of the insulator is more likely to

occur than direct dielectric puncture, unless a distinct flaw is present in the insulator. To prevent this and make the creepage distance greater the porcelain is very frequently "rippled." If however the ripples are very deep, with narrow air distances between the protuberances, the air in the trough may be again overstressed and surface creepage increased, so a shallowed rippled surface is often more advantageous than a deeply rippled surface.

The greatest concentration of dielectric flux is, at the uppermost point, where the conductor passes from porcelain of high dielectric strength to air of much lower dielectric strength. To prevent such sudden variation and discharge, it is customary to terminate the conductor by means of a metallic "hat." This is often a metallic sphere or better a large hat, as shown in Fig. 180, the purpose of which is to distribute the total electrostatic flux over the conductive metal of large surface area.

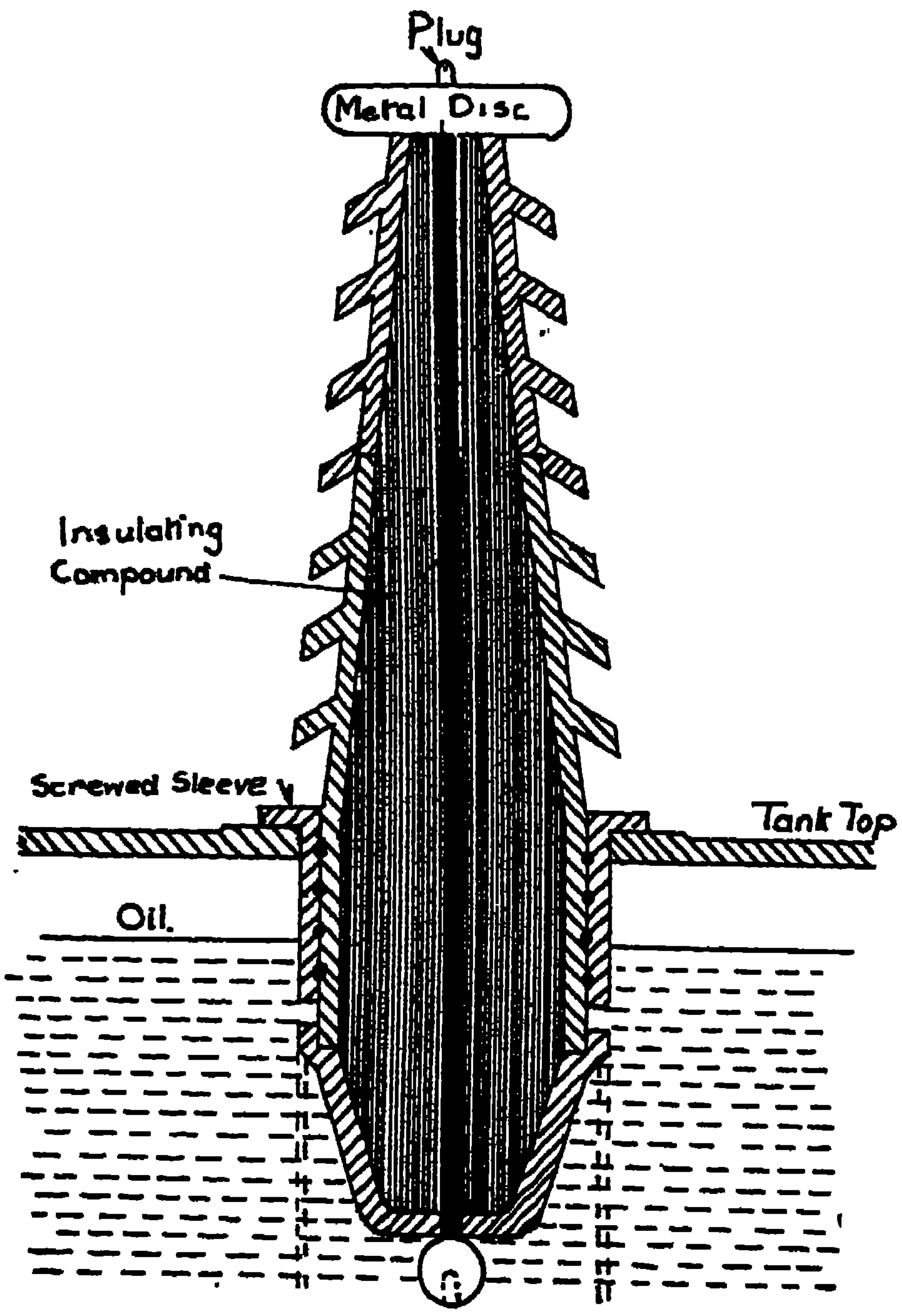


FIG. 180.—High-tension Insulator.

A further region of concentration of flux would occur at the bottom of the insulator, if this were in air. To avoid this the insulator is continued well below the surface of the transformer oil and often provided with a hat or boss, which can be of smaller dimensions than the upper hat, as the variation of dielectric capacity is less on entry to oil than on entry to air.

Whilst a rippled insulator surface tends to increase the creepage distance it also tends to provide a surface upon which conductive dust can collect in air and conductive oil sludge can collect in oil. The ripples should therefore be so designed to point downwards to minimise this defect. For this reason, a plain insulator is often preferable.

To overcome the possibility of defects in the insulating material, it is now common to make composite insulators of layers of insulation separated by conductive metal sheaths. These sheaths are so arranged as to occur at certain definite distances within the insulator and the edges to occur at definite positions of the insulator surface. Being conductive and

equipotential they then tend to distribute evenly the total potential, so that no excessive potential, likely to cause over-concentration of electrostatic flux, can occur.

The central conductor is also often within a wide-bore central channel filled with insulating oil. In this case it is imperative that the upper and lower portions of the insulator should have joints such that the oil cannot drain away and be replaced by a non-desired air dielectric.

The distance apart of the two terminals of the transformer should be at least 1·3 times that of the maximum sparking distance of the secondary voltage, but conveniently does not exceed this distance, as such a distance allows sparking if the transformer is over-excited, and so protects the secondary insulation from any greater over-tension. When the dimensions of the transformer tank are such as not to permit this distance being obtained by the open secondary leads being taken directly upwards, this distance may be obtained by sloping the insulators, as shown in Fig. 179, provided the distance apart at the lower ends of the terminals, beneath the oil, is still sufficient.

Wherever possible a direct lead-up is preferable, as inclined insulators tend to collect dust and so to cause creepage.

Dielectric insulator stresses in a transformer, of which the tank is earthed for protection, occur at the region where the insulator passes *viâ* the metal tank cover, since the total stress in then thrown across the insulator between internal high-tension conductor and external earthed tank cover. To avoid such concentration the tank cover is preferably made of insulating material, as paxolin, bakerlite, etc.

## TRANSFORMER OIL

The main requirements of the oil used in transformers are as follows ;—

(1) A large specific heat, in order to aid absorption of heat from the windings and core.

(2) A large dielectric strength, for reasons of insulation.

(3) Non-acidity, to prevent it corroding the insulation and the conductors.

(4) Low viscosity, to facilitate convection currents, to convey heat by this means of heat transference.

(5) Absence of moisture.

Transformer oil is usually a mineral oil the main functions of which is to provide a fluid dielectric capable of convection to remove heat. In the case of high-tension transformer oil it is of the utmost importance that all moisture be removed which would cause deterioration of the windings.

Further, no solid contaminating matter must be present which would be liable to be carried by convection between the windings, and so form conductive short-circuiting paths. For this reason in preparation

the oil is filtered by a special type of filter press through an absorbent, as blotting paper, which removes both moisture and solid impurities. Centrifugal separators are also used, but a description of such filtering and separating apparatus is beyond the scope of this book, and books on transformer practice must be consulted.

When the oil is run into the tank *in situ*, the oil is often heated to remove moisture in the transformer tank, either by applying heat from an external fire, etc., or, more safely, by placing electrical resistances conveying current in the tank. As such a procedure involves practical details regarding the maintenance of a constant temperature, the avoidance of mercury thermometers (with which, being liable to fracture, there is a danger of short-circuiting of the windings and of amalgamation) such drying processes do not fall within the scope of the radiologist.

A high-temperature transformer oil should have a dielectric resistance such that the breakdown pressure is not less than 50 kv. across a standard British testing gap of ·15 in. between ·5 in. diameter spheres. Two classes of oil are specified in the British standards, namely Class A and Class B. These two standards differ chiefly as regards the "sludge value," which is measured by maintaining the oil at 150° C. for forty-five hours, in the presence of bare copper foil, and bubbling air through the oil at a rate of ·07 cu. ft. per hour. This is an attempt to represent, in a comparatively short period, the sludging action which occurs in transformers operated over long periods above their normal temperatures (see British Standard Specification No. 148). The other requirements of these specifications are concerned with the absence of acid and sulphur compounds liable to cause corrosion, and details of viscosity, flash point, specific gravity, etc., which may be considered of secondary importance to the dielectric strength, heat capacity and sludge values.

The difference between Classes A and B oils does not affect X-ray transformers, which are unlikely to be operated over long periods, as in the case of power transformers, and so are not liable to attain excessive temperatures. It is therefore permissible to employ the cheaper Class B oil, since the most important factor, the dielectric strength, is the same as that of the Class A oil.

## THE TRANSFORMER TANK

This is by no means such an insignificant part of the transformer as might be expected. It should be made of welded wrought iron of about ⅛ in. thickness, and not merely bolted or riveted together, since such bolts, or other protuberances, act to alter the electrostatic flux density, even when the tank is large. A circular or oval tank (see Fig. 179) is preferable to the rectangular type tank, since these aid a more regular distribution of the electrostatic fields.

The heat generated in the coils by electrical resistance and in th core by magnetic hysteresis is conveyed by the oil to the tank and the radiated by the tank surface, which is a better radiator if of black or du finish.

Where large amounts of heat have to be radiated, as in large powe transformers, the determination of tank dimensions is by no means simple problem, but based upon scientific conceptions of heat conduction

The radiation of a tank increases approximately as the square of th surface area. Since the ratio of area compared to the volume is mucl larger with a small transformer tank than in the case of a large tank and as X-ray transformers can be classed as small transformers, the surfac area of the tank is usually quite sufficient to allow effective heat radiation without recourse to such additional methods of increasing the tank are by making the surface corrugated, or by incorporating in the tank side vertical tubular projections, in which the oil flows *viâ* convection and sc increases the cooling surface. In large power transformers it is alsc common to increase cooling by a circulating system of water pipes withir and insulated by the oil dielectric. This transformer method has beer applied to cool X-ray tube targets (see p. 122), but, as far as the writer is aware, not to cool the actual X-ray transformers.

The tank for an X-ray 10-kv.a. transformer should be capable of radiating 11 watts per square metre of surface for every temperature rise of 1° C. above normal temperature. This value in the case of small power transformers, as X-ray transformers, is reached by nearly any tank of convenient size. For example, in the case of the 250,000-volt transformer computed, a tank of 36 in. internal length, 25 in. internal breadth and 23 in. oil depth is sufficient.

Of more importance than heat radiation in the case of small transformers is the effect of the heat generated causing the expansion of the oil and, unless the tank is hermetically sealed, air above the oil is driven out. On cooling, air again enters the transformer and, being damp, this is to the detriment of the dryness of the oil. To prevent this, "breathers" (Fig. 181) may be fitted which cause all incoming air to pass over calcium chloride which, having great affinity for moisture, causes dehydration of the incoming air.

The expansion of the oil and the air above may be utilised to operate the closure of an electrical relay circuit, so that, in the case of an excessive temperature rise, due to any defect, the primary circuit is broken by the relay. An obvious method of doing this is by means of a U-tube containing mercury, expansion of the heated oil causing movement and, in turn, movement of the conductive mercury to bridge across contacts of a relay circuit. A further method is by means of a "Sylphon" chamber, as described upon p. 120.*

* British Thomson-Houston Patent, No. 160,019/1919.

Of great importance, and by no means yet recognised by many manufacturers, is the necessity of some form of safety valve, in case the transformer should break down and, as a result of the destruction of the oil,

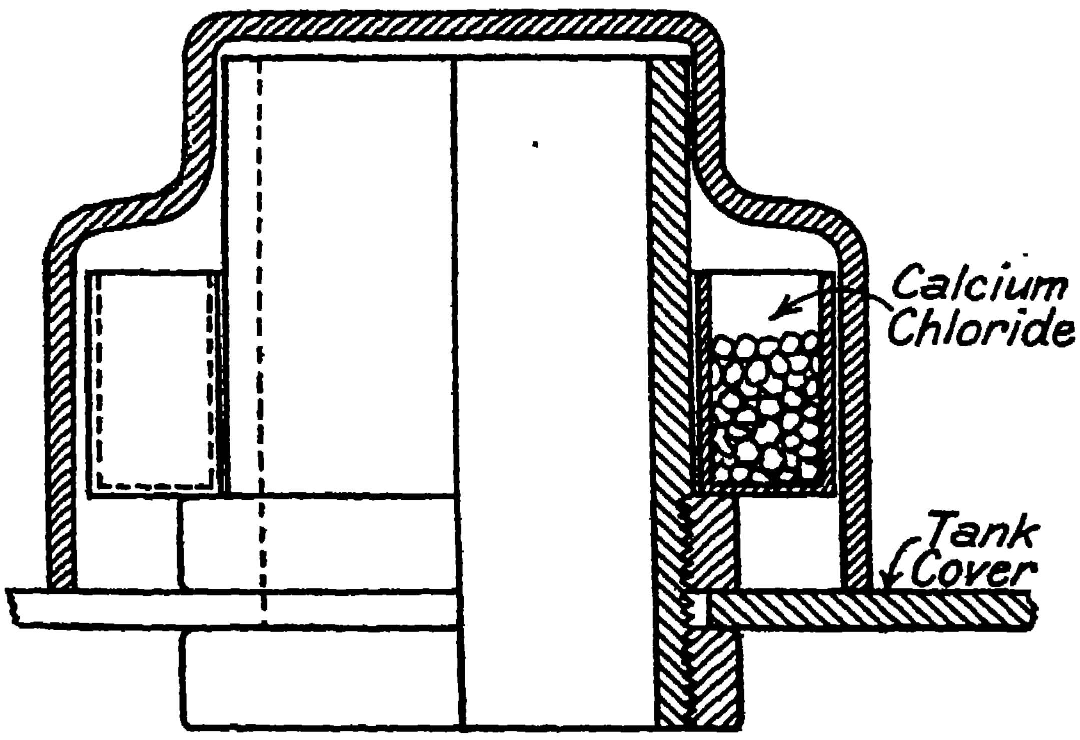



FIG. 181.—Transformer " Breather."

gases are generated which may give rise to a dangerous explosive internal pressure.

Such a safety valve may consist of a hermetically sealed, closed, light-metal foil diaphragm (Fig. 182, *a*) which will easily rupture should an excessive pressure occur, and is of such area as to allow the ready escape of gases and oil. A further type of safety valve, formed by a spring

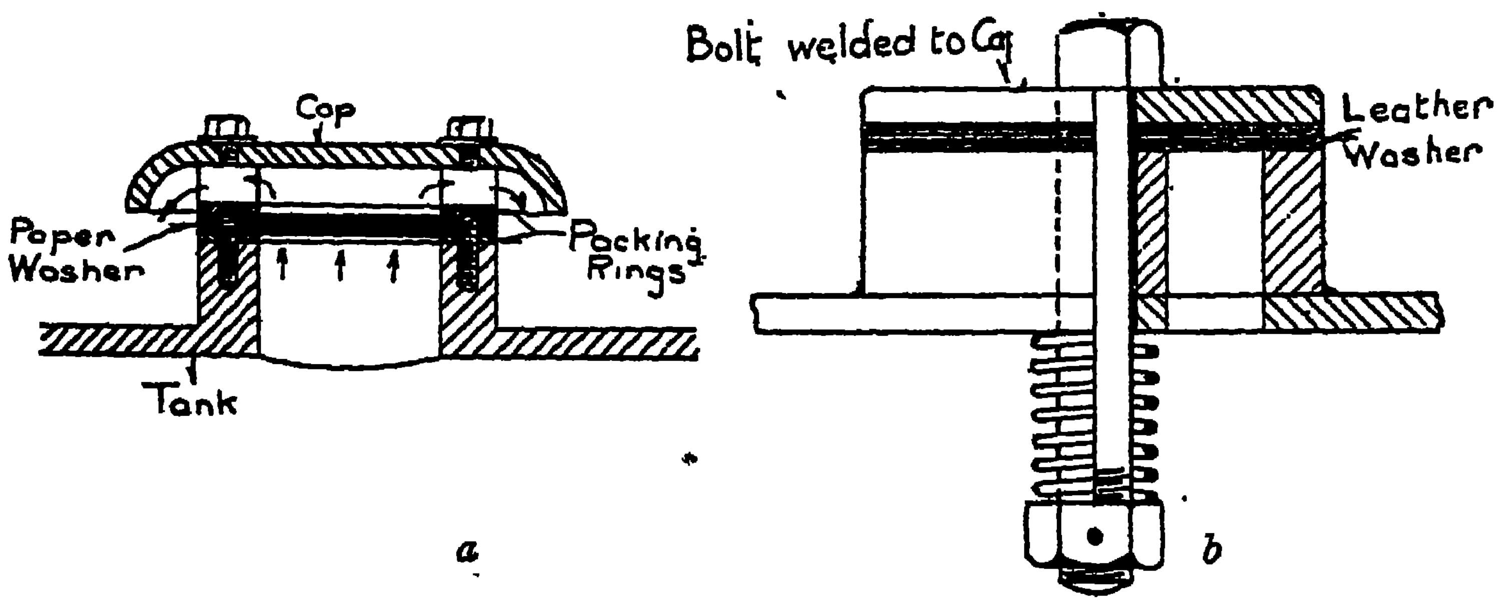



FIG. 182.—Safety Valves.

which holds down the diaphragm, but the force of which, in case of pressure rise, is easily overcome, is shown in Fig. 182, *b*.

For convenience the transformer tank may be mounted upon rollers if it is desired to move it. As the weight of a 10-kv.a. 250-kv. instrument, we have computed, will be in the neighbourhood of 3 cwt., this procedure will be rarely desired. Should the transformer be required to be movable it would be imperative that the earthing arrangements are capable of always being maintained, since, if this earth connec-

tion is broken, the dielectric materials will be subjected to at least twice the normal dielectric strain, and breakdown will be very liable to occur.

The advantage of an insulating tank cover over a metal cover has already been mentioned.

The details shown on p. 236 of four X-ray transformers (approximately 125 kv.) of varying English manufacture may be compared with our standard specification. In all cases the diameter of the core is below the recognised standard of 4 in. of normal transformer practice.

## THE EARTHING OF TRANSFORMERS

(1) *Earthing of Secondary Winding.*—The secondary winding of a high-tension transformer may be earthed in one of two ways ;—

(*a*) One end of the secondary is earthed.

(*b*) The mid-point of the secondary is earthed.

The first method is that usually employed in high-tension transformers intended for testing insulation, etc. Its object is that then the total secondary potential may be applied to a test object with only one high-tension connection. This has practical advantages, since it is then unnecessary to insulate the object to be tested from earth.

Such a unipolar method of use of transformers in X-ray technology is not uncommon, for example, in transformers intended to operate a dental X-ray tube where it is desired to approximate closely the tube to the patient. This is done by earthing the tube container and one end of the secondary winding of the transformer, the full potential being applied to the insulated anode, connected to the other secondary terminal of the transformer. Such unipole earthing promotes high-frequency surges.*

The object of the second method of earthing is entirely different. If the mid-point of the secondary is earthed then, since the potential developed by each secondary winding is independent of external conditions, whilst the potential of each limb with respect to earth is only say $n$, the potential between the two secondary terminals is $2n$. As the necessary insulation rapidly increases as the voltage rises, not directly, but as the cube of the voltage, then by earthing the mid-point of the secondary the insulation necessary is enormously decreased, *i.e.*, it may be represented by $n^3$ instead of $(2n)^3 = 8n^3$. As a consequence the size and cost of a high-tension transformer is enormously reduced if the mid-point is earthed, and this is a very common practice with high-voltage transformers, not designed for testing purposes but for such purposes as X-radiation generation.

The subsidiary advantages of earthing the mid-point of the secondary are, that any slight differences between the two limbs of the transformer are stabilised and that any undesired oscillatory surges in the winding

* Glocker and Kaupp, *Zeits. tech. Phy.*, 7, p. 438, 1926.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Core . . . . | About 3·5 in. diameter. Stalloy laminations of 0·5 mm. thickness (4 sizes). | $3\frac{7}{8}$-in. diameter. Yokes $3 \times 3\frac{3}{4}$ in. $B = 58{,}000$ lines per square inch. | ·02-in. stalloy laminations, diameter not given. | 3·5 in. diameter. Four sizes of stalloy laminations bolted by brass bolts with wooden cheeks. |
| Primary . . . | Single layer of No. 12 S.W.G. to total resistance of ·1728 ohms. | No. 12 D.C.C.—100 turns per limb. Total voltage per limb equals 115 volts. | No. 14 D.C.C.—220 turns wound in parallel. Total resistance equals ·14 ohms. | No. 12 D.C.C. turns $2 \times 93 = 186$. |
| Secondary . . . | No. 36 S.W.G. silk-covered subdivided sections (4). Approximately 60,000 total turns between varnished insulation. Total resistance 22,000 ohms. | No. 38 S.W.G. enamelled wire and protective windings of No. 20 D.C.C. at ends; 100,000 turns with total voltage 115 kv. (R.M.S.). In ten sections. | No. 36 S.W.G. enamelled wire graded at ends with No. 31 D.S.C., and finally No. 26 D.C.C. Total resistance 29,200 ohms. | No. 36 S.W.G. double silk covered, developed to 120 kv. |
| Major insulation . . | Paxolin tube, outer diameter 5 in. Glass plate insulation between limbs. Not vacuum dried. | Paxolin tube and oil. | Vacuum dried. | $\frac{3}{8}$-in. thick paxolin tube. $\frac{1}{2}$-in. glass sheet between limbs. $\frac{1}{2}$-in. ebonite and 3 in. of oil at high-tension ends. Vacuum dried. |

Details of Various X-Ray Transformers.

find a path to earth and are not so liable to build up in amplitude by resonance effects, with consequent danger to the insulation.

It has been suggested * that, by earthing the mid-point of an X-ray transformer or induction coil the shock and consequent danger to a patient or operator, by contact with the high-tension leads, is halved.

This is a purely theoretical advantage as, to take the case of the smallest type of X-ray transformer, giving about 60 kv., if the patient is well earthed, the effect of 30 kv. will undoubtedly be the same as that of 60 kv.

Such a view is entirely erroneous, as there can be no question that, by earthing the mid-point of a transformer secondary, the danger of accidental contact is greatly increased. If the mid-point is not earthed, the current path from one terminal in contact with the victim is *viâ* the victim to earth and back to the transformer *viâ* the transformer insulation. The latter, by its inherent resistance, therefore prevents any great flow of current. If the mid-point is earthed the current path is *viâ* the victim to earth and from earth back to the transformer *viâ* the earth connection of negligible resistance. The current flow may therefore be very large and far more dangerous than in the first case, where short circuiting cannot occur.

It would therefore certainly be more safe if diagnostic X-ray transformers were not of the mid-point earthed variety (as is always the case). The mid-point is only earthed to decrease cost of insulation and decrease the size but, as either requirement is not excessive for 125 kv., this hardly appears warranted in view of the dangers of this practice.

(2) *Earthing the Primary Winding.*—In all high-tension transformers the primary winding should be earthed as, should the insulation between primary and secondary breakdown, the dangerous high-tension can then find a ready path to earth and there is less danger to a patient or to an operator (who may be operating the low-tension controls upon the switchboard) than in the case where the low-tension circuit, is not earthed Before earthing the low-tension primary circuit, it is however wise to ascertain if this circuit is already earthed as, in this case, heavy circulating currents may be set up between the two earthed points.

## SUBDIVISION OF TRANSFORMERS

A well-designed transformer is intended for definite primary and secondary voltages and only minor variations of the low-tension voltage are permissible. It is quite simple to wind the primary circuit with double conductors and to arrange to connect differently these parallel

* *Jour. Ront. Soc.*, 17, p. 12, 1921.

windings to allow the use of the instrument on two voltages, such as 110 and 220 volts circuits.

The subdivision of the secondary circuit, *i.e.*, to obtain both 125 kv. and 250 kv., is however rarely advisable, since, to obtain the lower voltage, this means that only one-half of the windings will be active and the idle half may produce "dead-end" effects. By suitable resistances or, better, auto-transformer controls in the primary circuit a wide variation of the secondary voltage can be obtained. Such a method is generally preferable to any method of tapping the secondary circuit.

Tappings for such a purpose, which should be connected under oil, lead to greater internal complexity of the transformer, with consequent risk of short-circuiting and breakdown. Also in the "dead ends" so left by the non-active windings, high-frequency surges are liable to occur and, since there is no "load" for this dead end, very heavy circulatory currents will be set up.

## TRANSFORMERS FOR THE SUPPLY OF CURRENT TO THE HOT CATHODE OF THE ELECTRON X-RAY TUBE

The most common method of energy supply to heat the filament of a hot cathode tube is by use of a suitable transformer. Whilst this method has disadvantages due to the periodic variation of the alternating current, it has great advantages as regards convenience.

Such transformers are "step-down" instead of "step-up" transformers to transform, in the case of the Coolidge tube, a main voltage of say 200 volts, down to about 12 volts, with a current supply of about 5-6 amperes, and an energy output of 60 watts. Such transformers are often non-iron core transformers, the primary and secondary being wound upon an insulating sleeve (Fig. 119).

In the design of such transformers of the closed-core oil-immersed type, no special features arise except that of the high insulation between primary and secondary. This is most necessary, as the filament of the X-ray tube is in the high-tension circuit. It is therefore imperative to prevent any short circuit between the high-tension secondary and the low-tension primary. This is obtained by means of a paxolin or porcelain sleeve of suitable thickness, usually about $\frac{1}{4}$ in. to $\frac{3}{8}$ in.

It is common to mount, upon a suitable high-tension insulator above the transformer case, an ammeter to indicate current strength (0 to 6 amperes) which is in the secondary circuit, the primary circuit current consumption being below 1 ampere (about ·3 amperes on a 200-volt circuit).

Other than the above special insulation these transformers offer no special features.

## THREE-PHASE TRANSFORMERS

Since three-phase excitation has been applied to X-ray tubes, to provide a more or less steady potential supply, as contrasted to the fluctuating single-phase supply, these need brief mention.

They offer no special features as regards design. The smaller three-phase transformers are often wound upon a common three-limb core (Fig. 183) in order to economise iron, the middle limb having a larger cross-sectional area, since it carries twice the current and magnetic flux of the outer limbs.

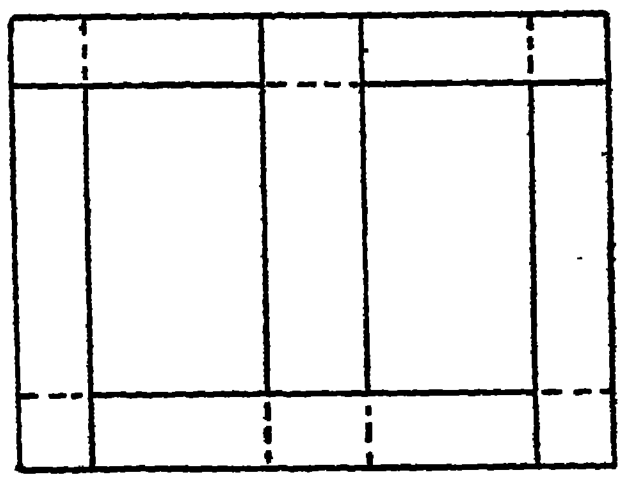


FIG. 183.

In higher power three-phase transformers this common three-limb core is not greatly used, and the transformation is carried out by three single-phase transformers, giving better and more efficient heat radiation as well as facilitating replacement and repair in case of breakdown.

High-tension three-phase X-ray transformers would be similarly best formed by three separate single-phase transformers in order to overcome the difficulties of extra insulation to separate the windings of the various phases. Their design would therefore resolve into the design of single-phase transformers. Irrespective of the mode of connection of the primary windings, the secondary windings can be connected in star, mesh, or more complicated connections as desired. As the mid-point (not the neutral point) of any particular transformer cannot be earthed, the advantages of such earthing as regards insulation cannot be obtained. If desired, by specific secondary connections, such a method of transformation could be utilised to triplicate the secondary frequency (see p. 183, Vol. I.).

## AUTO-TRANSFORMERS

Auto-transformers (see Appendix III.) are used in X-ray apparatus in order to regulate more economically and more gradually (than with resistance control) the voltage applied to the primary of the high-tension transformer and therefore in turn the voltage of the secondary of this transformer.

Since it is a low-tension transformer the insulation offers no especial features. This insulation is between the core and the single winding only, and would follow the scheme of the insulation between primary winding and core of the high-tension transformer already mentioned.

The core cross section is based upon similar considerations and is at least of 4 in. diameter but is usually greater and very often of square form. The dimensions C and L are generally considerably smaller. The

single winding is heavy gauge wire (as No. 12 D.C.C.) and is often layer wound with intervening Empire cloth insulation. This winding is tapped at specified intervals to give the necessary secondary tappings.

## PRESENT LIMITS OF TRANSFORMATION

By the fundamental Einstein-Planck relation ; $Ve = h\nu$, we see that the frequency, or quality of radiation $\nu$ is proportional to the voltage V. Knowing the value of $\nu$ for the radiation from radioactive substances, we find that this corresponds to voltages of excitation ranging from 1,000,000 to 2,000,000 volts.

Whilst we have, at present, no X-ray tube able to operate above 250 kv., given a suitable tube there is little doubt that $\gamma$-radiation could be excited, and the question therefore arises as to the possibility of exciting the necessary voltages.

Within the last few years voltages of over 2,000,000 volts have been excited. All such methods of voltage transformation depend upon "stepped" transformers. This method of high-voltage excitation was suggested by Steinmetz in America no less than twenty-five years ago, was used in France by Verdovelli in 1907, and by Fischer* in Germany in 1912.

It was developed by Dessauer † in 1914–15 and has been used to construct deep-therapy apparatus by the company with which Dessauer is associated.

In this method, instead of transforming the voltage direct from low-pressure values of, say, 200 volts to high pressure values of, say, 250,000 volts, the transformation occurs in several stages which at the higher tension stages do not exceed a ratio of 2.

An example of such transformations due to Dessauer is shown in Fig. 184.

The advantages of such a method is that, as there is not at any stage any very high ratio of primary and secondary voltage, difficulties of major insulation between these circuits do not arise.

Whilst such a method allows reduction of insulation in one sense, the total insulation of the various subsidiary transformers must tend to equal the insulation of a lesser number of transformers, with higher ratios of transformation. Further, it is necessary to insulate more heavily each primary winding from the iron core, although this is greatly reduced by totally insulating the various subsidiary transformers.

An advantage obtained with such multiple stepped transformers is

* *Elek. tech. Zeits.*, 33, p. 885, 1925.

† F. Dessauer, *Verh. der. deut. Phys. Ges.*, 19, p. 155, 1917. *Elek. tech. Zeits.*, 44, p. 1087, 1923. Brit. Patent 155,830/1920. Dessauer gives in his paper a method of testing the dielectric properties of an insulating material without incurring its actual breakdown. If the small electrostatically transmitted (displacement) current is plotted against applied voltage, with increase of voltage the relation takes a straight-line course, until the limits of the dielectric stress being approached, this straight-line course begins to acquire curvature, showing the commencement of insulation breakdown, although actual breakdown may not be imminent.

that of facility of repair of any component transformer, in case of breakdown. Efficient cooling of the cores and windings is also produced by this method of construction, but the overall losses are higher according to Lilienfeld,* who states the overall efficiency is only 60 to 70 per cent., as compared to normal values of 95 per cent. and upwards. Dessauer appears however to use open-core transformers, and doubtless the efficiency would be much greater with closed-core transformers.

The great advantage of this type of transformer is that, since the insulation increases as the cube of the voltage difference between primary and secondary, the insulation cost and risk of breakdown is much lower if such voltage differences are decreased by utilising several steps of lower voltage difference. The cost however increases owing to the construction

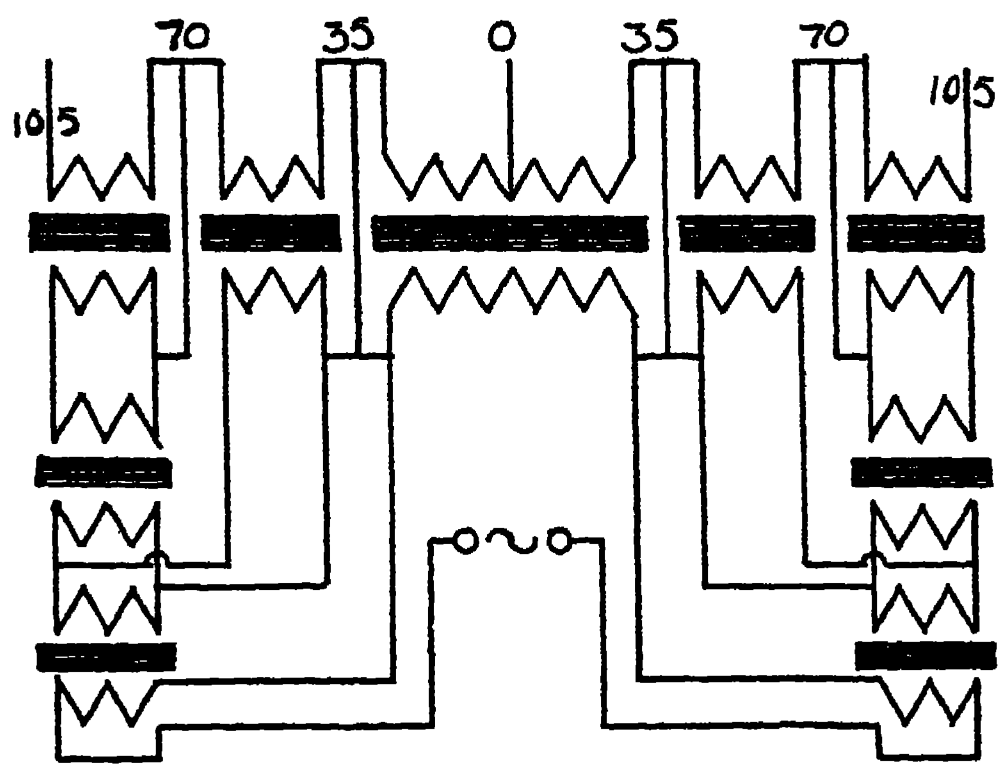



FIG. 184.—Diagram of Dessauer Transformer.

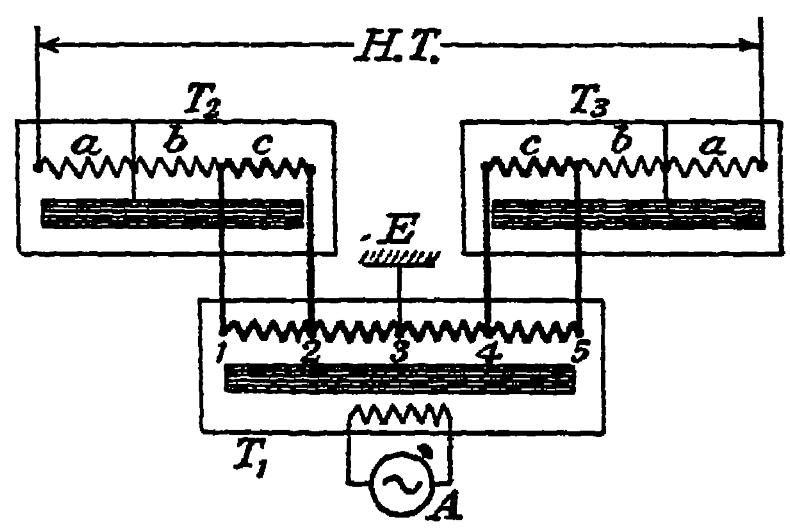



FIG. 185.—Stepped Auto-transformer.

of a number of transformers with this method, but apparently the first advantage predominates.

The advantage of earthing the mid-point is retained in the Dessauer transformers but, since the intermediate stages are not earthed, very heavy circulatory currents may be set up in these, if the various transformers are not accurately balanced. Doubtless the lowered efficiency is to be traced to such circulatory currents very liable to develop " hot spots," to prevent which Dessauer joins the mid-points of each primary and secondary winding.†

Auto-transformer connection (Fig. 185) is sometimes used ‡ with the mid-point of the secondary earthed, in order to overcome the necessity of insulating primary and secondary windings.

Of the various very high-tension transformers described in the technical journals, the descriptions are invariably descriptive only and give no intimate constructional details. Perhaps the only exception to this

* *Verh. der. deut. Phys. Ges.*, 20, p. 159, and 20, p. 265.
† Brit. Patent 155,831/1920.
‡ Brit. Patent 155,832/1920.

is a transformer constructed by K. Fischer * of the Aix-la-Chapelle Technical High School. This is designed for a voltage of 500 kv. for testing purposes, given by two 250-kv. transformer units, an example of one of which is shown in Fig. 186.

This transformer is remarkable, as it differs from normal transformer standards in ;—

(1) Being of the dry type, *i.e.*, not oil-immersed.

(2) It is layer wound and not, as usual, sectionally wound.

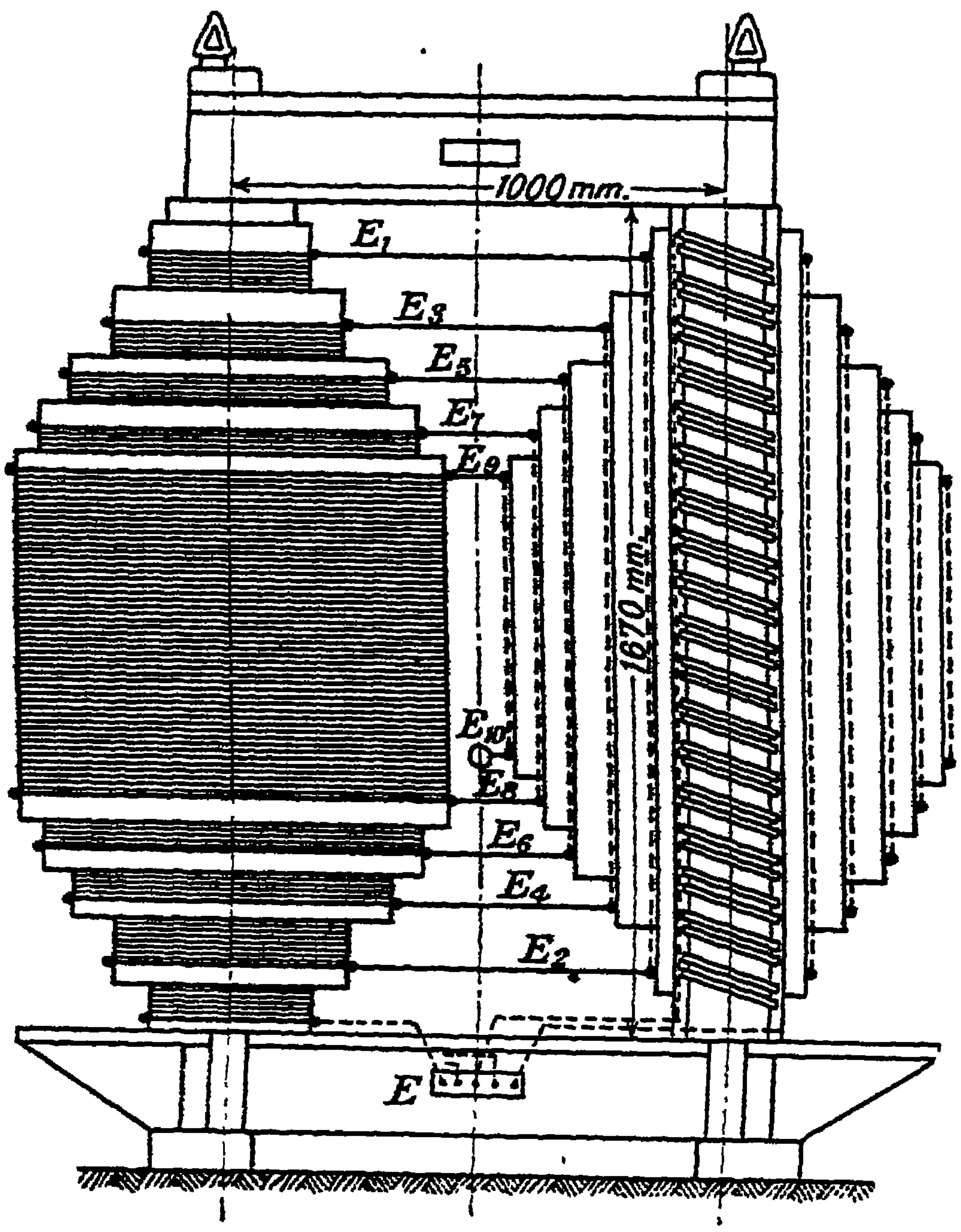



FIG. 186.—Fischer 250-kv. Air-cooled Transformer.

The core has limbs of 205 mm. diameter and 1,670 mm. length. The low-tension winding consists of twenty-one turns per limb of two flat wires in parallel, each of ·8 mm. area. Over the low-tension winding are two paxolin (hard paper) cylinders, of thickness 3 mm.

The core weighs about 1,000 kg. and has no-load iron losses of 3,310 w.

The special feature is the high-tension winding, which is built in steps and is wound by single layers upon concentric insulating paper cylinders of varying diameter. For the secondary winding enamelled wire of ·15 mm. diameter is used. These cylinders are machine wound to give thirty-nine turns per centimetre length. With normal excitation the volts per turn are 5·5, and therefore, per centimetre, $39 \times 5{\cdot}5 = 214$ volts. The first cylinder has a total length of 1,620 mm. and is wound over 1,610 mm., with a clearance of 60 mm. from the yoke. The total voltage developed by this cylinder's winding is 34·5 kv., it having a diameter of 310 mm., and is so chosen that the flux density between its point of highest potential and the core does not exceed 8 kv./cm.

This first cylinder is connected in series with a similar cylinder on the other limb, this series connection being by a permanent connection parallel to the yokes, the scheme of connections of the five pairs of windings of diminishing number and length being shown in Fig. 186. These various cylinders are kept at rest, relatively to each other, by Pertinax

* *Elek. tech. Zeits.*, 46, p. 186, 1925.

struts. The greatest difficulty in construction was the tendency to brush discharge and arcing between the end windings of neighbouring cylinders. As this discharge is dependent upon the small diameter and great curvature of the thin enamelled wires, such brush discharge was prevented by the use of a metal ring at the winding end, as shown in Fig. 187.

Fischer claims that by the layer winding many difficulties of coil winding are decreased. The last cylinder has to prevent breakdown due to surges, and its winding is reinforced for a distance of 15 cm. from the end. The windings are caused to adhere to the cylinders by shellac adhesive, and the finished winding is coated with dark, air-free lacquer and, under these conditions, can carry a secondary current of 10 amperes per square millimetre of section, without fear of disengagement of the winding by heat. The brush discharge is so little that at full load it can only be seen in darkness at the terminal rings, and a test overload led to no defects. The constructor particularly accentuates the advantages of layer winding for both dry and oil transformers. The above transformer, whilst designed for test purposes, would appear to be of quite suitable dimensions for X-ray purposes.

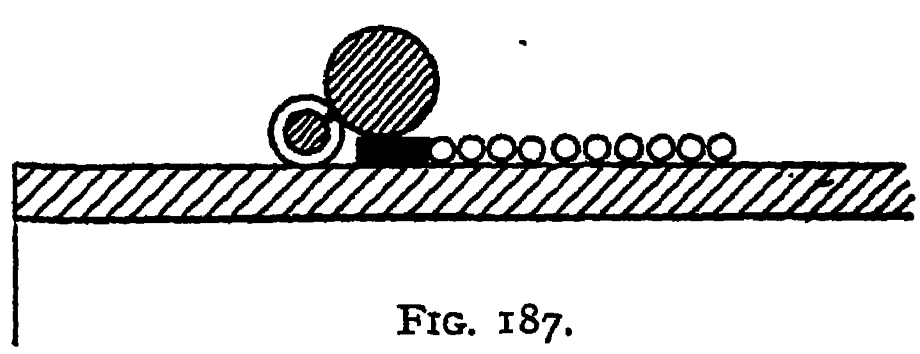


FIG. 187.

The remaining high-voltage transformers which have been described are of very large dimensions. They are designed not for the very short intermittent loads of X-ray practice, but for heavy permanent loads to test commercial insulators, etc., and their dimensions only permit their use in special laboratories.

It is of interest to note that abroad, within the last few years, heavy load transformers for 120 kv. have been mass-constructed and used. From the secondary mains of such transmission systems an X-ray tube for diagnostic purposes could be directly excited. This limit of commercial transmission has been still more raised to 220 kv. by the American General Electric Company, for an installation of the South California Edison Company * and information is to be found in the reference of such transformers, each dealing with 8,333 kv.a.

Transformers for 1,000,000 volts have been constructed for insulator testing by Messrs. Koch & Sterzel † in Germany, and by Messrs. Ferranti ‡ in England, who have used the stepped method.

A similar voltage three-step transformer has been constructed at the Ampere Laboratory at Ivry-sur-Seine § and a very complete

* C. Jonas, *Gen. Elect. Rev.*, p. 399, 1921.
† *Elek. tech. Zeits.*, 45, p. 177, 1924.
‡ E. T. Norris, *Electrician*, 94, p. 456, 1925.
§ d'Arsonval, *Comptes Rendus*, 177, p. 1429, 1923. R. B. Matthews, *Elect. Review*, 94, p. 124, 1924.

description of this installation, which required a specially built laboratory, is given by J. Reyval,* who also refers to other high-voltage installations.

The American General Electric Company have constructed a 1,000,000-volt transformer which has been used by Peek † for the purposes of testing insulators, who gives details of this transformer. More complete details and experimental tests have been given by Hendricks ‡ who, by grouping several such transformers in three-phase connections, has obtained voltages of 2,250,000 peak volts, giving sparks over distances of 14 ft., and which, given a suitable tube, should be quite sufficient to generate directly radiation similar to the radium $\gamma$-radiation.

These transformers are 500 kv.a. and are peculiar in their secondaries, being wound of thirty miles of aluminium strip and not of copper. Such a winding has a large capacity and, in consequence, the current is not, as usual, lagging behind the voltage, but is actually advanced in phase. The complete transformer has three steps, the first being for a 2,500/578,000 transformation, the whole being immersed in an oil tank 26 × 16 × 14 ft. holding 36,000 gallons of oil. The insulation is of concentric cylinders of oiled pressboard, and the windings consist of fifty double-section coils, each coil being double taped with varnished cloth.

One pole is earthed *viâ* an ammeter and the high-tension pole is within the oil vat, and carries a very large aluminium sphere to prevent brush discharge.

## CALCULATIONS OF TRANSFORMER VALUES

The calculation of transformer efficiencies, regulation, impedance and reactance are not likely to be of great interest to the purely medical radiologist, but, to complete our survey, in the interests of the technician, these will be given for the case of the 250-kv. transformer already considered.

*Efficiency* does not need further explanation and is given by ;—

$$\text{efficiency} = \frac{\text{output}}{\text{output} + \text{losses}}$$

or

$$\left(1 - \frac{\text{per cent. iron loss} + \text{per cent. copper loss}}{100 + \text{per cent. iron loss} + \text{per cent. copper loss}}\right) \times 100$$

and is, for various loads, as follows ;—

| Load fraction. | $\frac{1}{1}$ | $\frac{3}{4}$ | $\frac{1}{2}$ |
|---|---|---|---|
| Iron Loss, per cent. .. | 2·1 | $\frac{3}{4} \times 2{\cdot}1 = 2{\cdot}3$ | $\frac{2}{1} \times 2{\cdot}1 = 4{\cdot}2$ |
| Copper Loss, per cent. | 2·26 | $\frac{3}{4} \times 2{\cdot}26 = 1{\cdot}7$ | $\frac{1}{2} \times 2{\cdot}26 = 1{\cdot}18$ |
| Total Loss, per cent. .. | 4·36 | 4·5 | 5·33 |
| Efficiency .. .. | 95·82 per cent. | 95·69 per cent. | 94·94 per cent. |

* J. Reyval, *Rev. Gen. d'Elect.*, pp. 847, 885, 1925.
† F. W. Peek, *Gen. Elect. Rev.*, 25, p. 111, 1922.
‡ A. B. Hendricks, *Jour. Amer. Inst. Elect. Engs.*, pp. 775, 876, 1922. *Gen. Elect. Rev.*, 25, p. 737, 1922.

Performances are usually given at 15·5° C., and the copper loss figures are inserted for this temperature. If required at any other higher temperature, the copper loss should be increased by ·4 per cent. of its own value. This is a fairly close approximation, but not an exact correction factor, as the eddy current losses decrease somewhat, due to increase of copper resistance with temperature. Where eddy current loss is small (50 cycles) this can be neglected.

*Regulation.*—When the secondary terminals of a transformer are connected with the load (X-ray tube), current flows in the secondary windings. As a result a magnetic field is produced in the core which is opposed to the field due to the primary circuit.

The secondary voltage is consequently reduced, until the primary current increases to produce a more intense magnetic field, sufficient to overcome this reduction. The ability of the transformer to vary the energy taken from the mains is called the *regulation* and is of importance, since if the regulation is not efficient, a steady secondary output is not maintained.

The value of regulation is given by ;

$$\text{per cent. regulation} = \mathrm{R}\cos\theta \times \mathrm{X}\sin\theta + \frac{(\mathrm{X}\cos\theta - \mathrm{R}\sin\theta)}{200}$$

where R = per cent. total copper loss.
X = per cent. reactance.

At unity power factor (see Vol. I.), $\cos\theta = 1$, and

$$\text{regulation} = \frac{\text{copper loss (watts)} \times 100}{\text{kilovolt-ampere output} \times 1{,}000} + \frac{2}{200}$$

which, for low-reactance transformers, may be reduced to ;—

$$\text{per cent. regulation} = \frac{\text{copper loss (watts)} \times 100}{\text{kilovolt-ampere output} \times 1{,}000}.$$

Inserting our values at 15·5° C.

$$\text{per cent.} = \frac{226 \times 100}{10 \times 1{,}000} = 2{\cdot}26 \text{ per cent.}$$

The same formula holds good for fractional loads, and it is only a case of inserting appropriate values of copper loss and output.

*Reactance.*—(See p. 130, Vol. I.)

The percentage reactance, at 50 cycles, of a core-type transformer with concentrically wound windings is given by ;

$$\mathrm{X} = \frac{\mathrm{IT} \times \mathrm{M}t}{\mathrm{V/T} \times \mathrm{L}}\left(a + \frac{b_1 \times b_2}{3}\right) \times 10^{-3}$$

where X = per cent. reactance.
IT = Total ampere turns in one winding on one limb.
V/T = Volts/turn.
L = Axial length of windings, in inches.
$a$ = Radial distance between high-tension and low-tension windings, in inches.
$b_1$ = Radial depth of low-tension windings.
$b_2$ = Radial depth of high-tension windings.

and, in our given case ;

$$\mathrm{X} = \frac{(45{\cdot}5 \times 69) \times 20{\cdot}05}{1{\cdot}6 \times 17}\left(1{\cdot}265 + \frac{{\cdot}26 + 1{\cdot}15}{3}\right) \times 10^{-3}$$

$= 4{\cdot}02$ per cent. at normal full load.

*Impedance.*—(See p. 130, Vol. I.)
The percentage impedance Z is given by ;—

$$\begin{aligned} Z &= \sqrt{R^2 + X^2} \\ &= \sqrt{(2{\cdot}26)^2 + (4{\cdot}02)^2} \\ &= 4{\cdot}61 \text{ per cent. at normal full load.} \end{aligned}$$

## TESTS

The tests usually carried out upon transformers are ;—
(1) Ratio test.
(2) Copper loss and impedance tests.
(3) Insulation resistance test.
(4) Iron loss and magnetising current test.
(5) Pressure test.

(1) *Ratio Test.*—The diagram of connections for this test is shown in Fig. 188. The test is usually made with the transformer out of its tank and in air. The method used is known as the *ratiometer method.* The ratiometer itself consists of a single-phase, double-wound transformer, having a constant primary winding and a variable secondary winding, the pressure variation being effected by the adjustment of tappings on two dial switches. A certain number of the secondary tappings are arranged to give fine regulation and the remainder coarse regulation. In carrying out the test the high-tension winding of the transformer under test is connected to the two free terminals of the dial switches, through an ammeter. A single-phase pressure, not exceeding 2,000 volts, is applied across the primary winding of the ratiometer, and the two dial switches are varied until the ammeter registers zero. The pressure across the low-tension winding of the transformer under test is therefore equal to the pressure across the effective part of the secondary winding of the ratiometer, *i.e.*, that part of the winding between the two switch terminals.

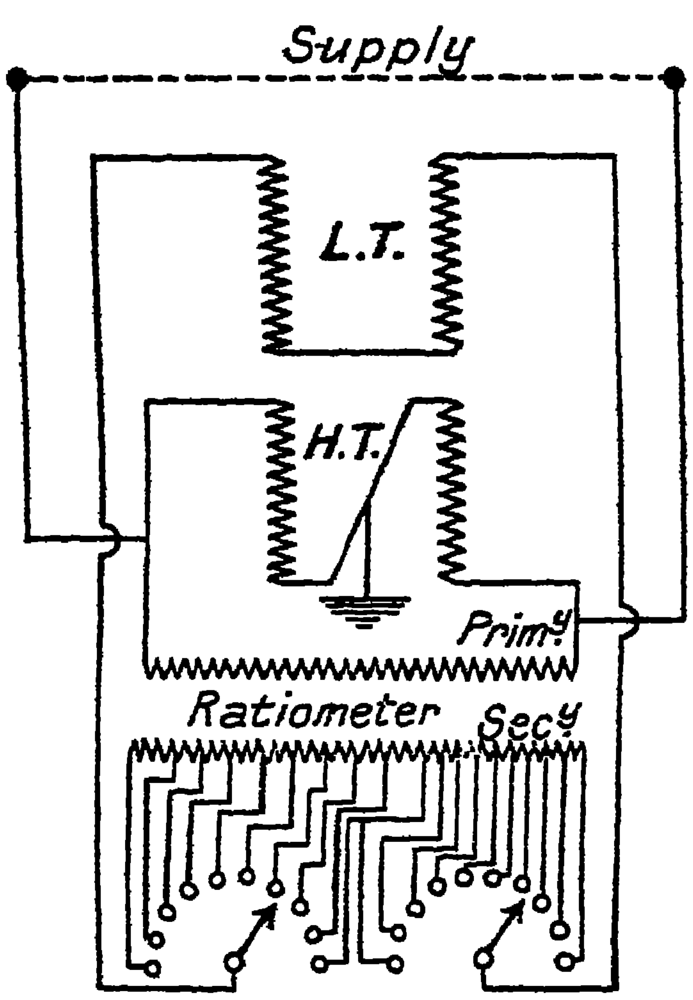


FIG. 188.

As the pressure across the high-tension winding of the transformer and across the primary winding of the ratiometer is the same, the ratio of the transformer must equal the ratio of the ratiometer. The actual voltage is determined by multiplying the test ratio by the specified transformer low-tension phase pressure.

Another method of measuring this ratio of primary to secondary pressure for very high tension transformers, is by direct measurement of the secondary voltage for a given primary voltage, by means of a standard sphere spark gap, or, still more accurately, by use of an X-ray spectrometer determining the quantum limit and use of the Einstein-Planck equation $Ve = hv$.

This method is stated by Kaye to be our most accurate method of voltage measurement, but it should be thoroughly realised that a spectrometer merely

measures the voltage on load and not necessarily the no-load maximum voltage. These voltages, particularly in an X-ray circuit, may materially differ (see Fig. 245).

(2) *Copper Loss and Impedance Tests.*—These two tests are carried out together and the connections are as shown in Fig. 189. Pressure is applied to the low-tension winding, the high-tension winding being short-circuited. Pressure is first applied to the low-tension winding at an initial value which is a fraction of the calculated impedance voltage.

The applied pressure is gradually raised, until the ammeter in the low-tension circuit registers the normal full-load current, when wattmeter, ammeter and voltmeter readings are taken. These readings complete the test, and the total copper loss is that given by the voltmeter reading. The impedance voltage is given by the voltage reading across the lines. It is important that a copper loss test should be carried out at the frequency for which the transformer is designed, as the frequency affects the eddy current loss component, though not affecting the $I^2R$ losses. The test is conducted with the transformer out

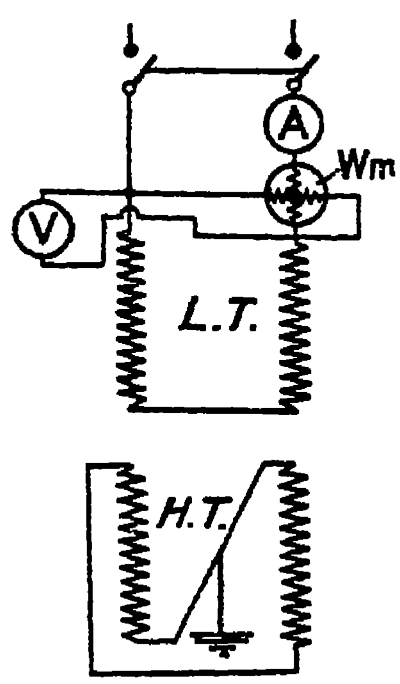


FIG. 189.

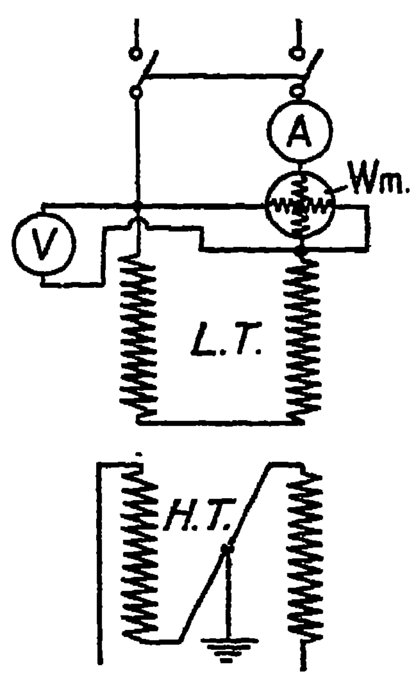


FIG. 190.

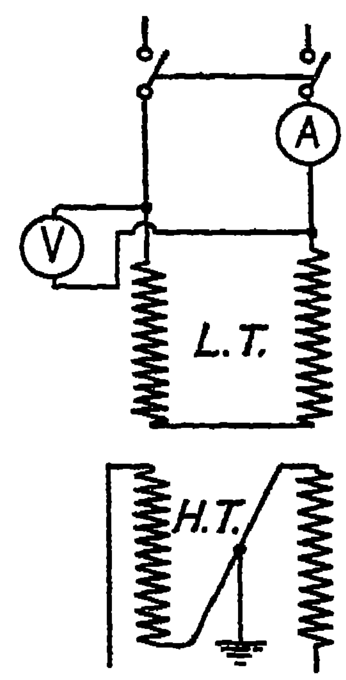


FIG. 191.

of its tank, as no high voltages are present which might otherwise strain the insulation.

(3) *Insulation Resistance Test.*—Insulation resistance tests are carried on both windings. The standard "Megger" testing set is used, the "live" terminal of which is connected to the winding under test, and the earth terminal being connected to earth. When making the test on the windings, so long as the limbs are connected together, it is only necessary to make one connection between the "Megger" and the whole of the windings. The high-tension and low-tension windings are of course tested separately. In either case the procedure is identical.

(4) *Iron Loss and Magnetising Current Tests.*—These two tests are also carried out together. The connections are shown in Fig. 190. The rated low-tension pressure at the specified frequency (both of which have previously been adjusted to the correct values) is first applied to the low-tension windings and then slightly readjusted. Wattmeter, ammeter and voltmeter readings are then taken. These readings complete the test, and the total iron loss is that given by the wattmeter reading. The magnetising current is given by the ammeter reading. This test is conducted with the transformer in its tank of oil.

(5) *Pressure Tests.*—The high-tension and low-tension windings of all transformers should be adequately pressure-tested before leaving the factory. These tests consist of what are known as (*a*) flash test, (*b*) overpotential test.

If the winding is designed for an earth connection the flash test, *i.e.*, the increase of primary voltage until a spark flashes over across the secondary terminals, cannot be applied and the overpotential test only is given. Fig. 191 shows the diagram of connection for the overpotential test, which is made by supplying the specified test pressure to the low-tension winding through a high-tension testing transformer and at a frequency higher than that for which the transformer under test is designed. For X-ray transformers it is not necessary to apply an overpotential test greater than 1·25 times the normal working pressure for one minute. The high-tension winding is left open-circuited, the test pressure being applied to the low-tension winding and induced in the high-tension winding. The pressure is measured on the low-tension side of the transformer under test direct. These tests are of course carried out with the transformer in its tank full of oil.

## EXERCISES ON CHAPTER IV

*Questions* 1 *and* 2 *are based upon analogous questions set in the D.M.R.E. Examination of Cambridge.*

(1) Describe the construction and action of a high-tension transformer for X-ray purposes. Why must the secondary current be rectified, and how is this carried out?

(2) What is meant by Ohm's Law? The primary resistance of a high-tension transformer is ·5 ohm when measured with direct current by a Post Office box. On 200-volt (50-cycle) mains the current is ·5 ampere on open circuit and 5 amperes when operating an X-ray tube. How do you explain this? What is meant by "regulation" of a transformer?

(3) In radiological examinations questions have been set as "Describe the direct current high-tension transformer." Discuss the advisability of the use of the term "transformer" for direct current apparatus.

(4) Describe fully the high-tension transformer to work from alternating current mains and include diagrams. (Soc. of Rad. Exam., December, 1923, and December, 1925.)

(5) Make a diagram of the high-tension transformer. (Soc. of Rad. Exam., January, 1922.)

(6) Give the considerations which arise in the design of (*a*) the core, (*b*) the primary circuit, (*c*) the secondary circuit, of an X-ray high-tension transformer.

(7) What protective devices should be fitted to the tank of a high-tension transformer?

(8) What are the advantages and dangers of earthing the mid-point of (*a*) the primary circuit, (*b*) the secondary circuit, of a high-tension transformer?

(9) Describe the advantages of the Dessauer type of subdivided transformer.

(10) Describe the construction and action of (*a*) a Coolidge filament transformer, (*b*) an auto-transformer for the control of an X-ray high-tension transformer.

(11) Contrast the advantages and disadvantages of oil- and air-cooled transformers.

(12) Describe various methods of freeing high-tension windings from air and risk of resulting corona.

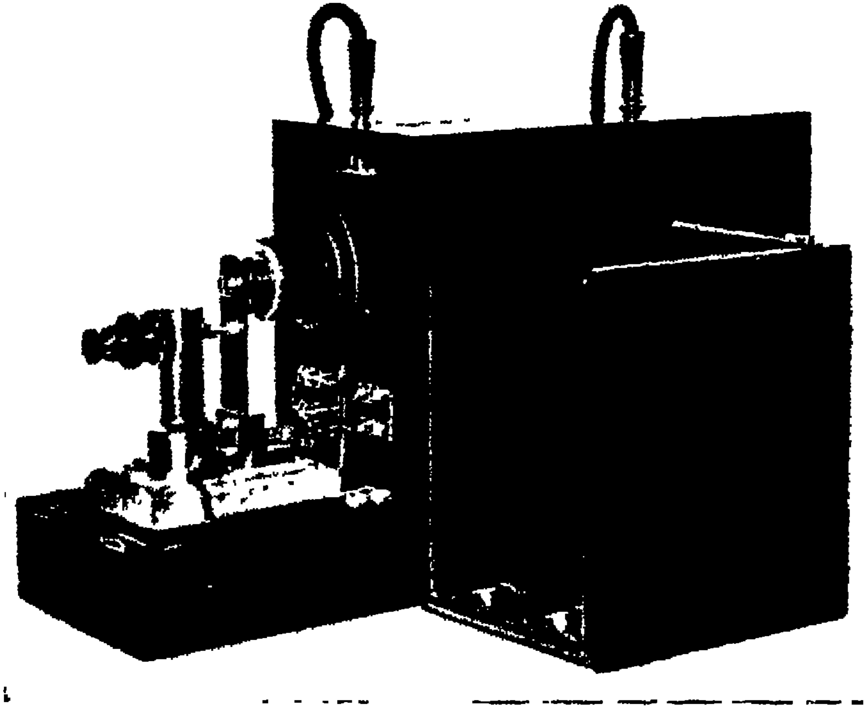


FIG. 192A.—Induction Coil with Hammer Break.

# CHAPTER V

## THE INDUCTION COIL

*Historical.*—The induction coil in its modern design, as in most inventions, represents a gradual development.

Faraday, in 1831, discovered the inductive effects of electrical currents and constructed the first transformer.

Henry, in 1832, and Dal Negros, in 1833, showed that when an inductive circuit was broken a spark was produced, and in 1835 Henry showed that a much greater spark resulted if the wire of the circuit was

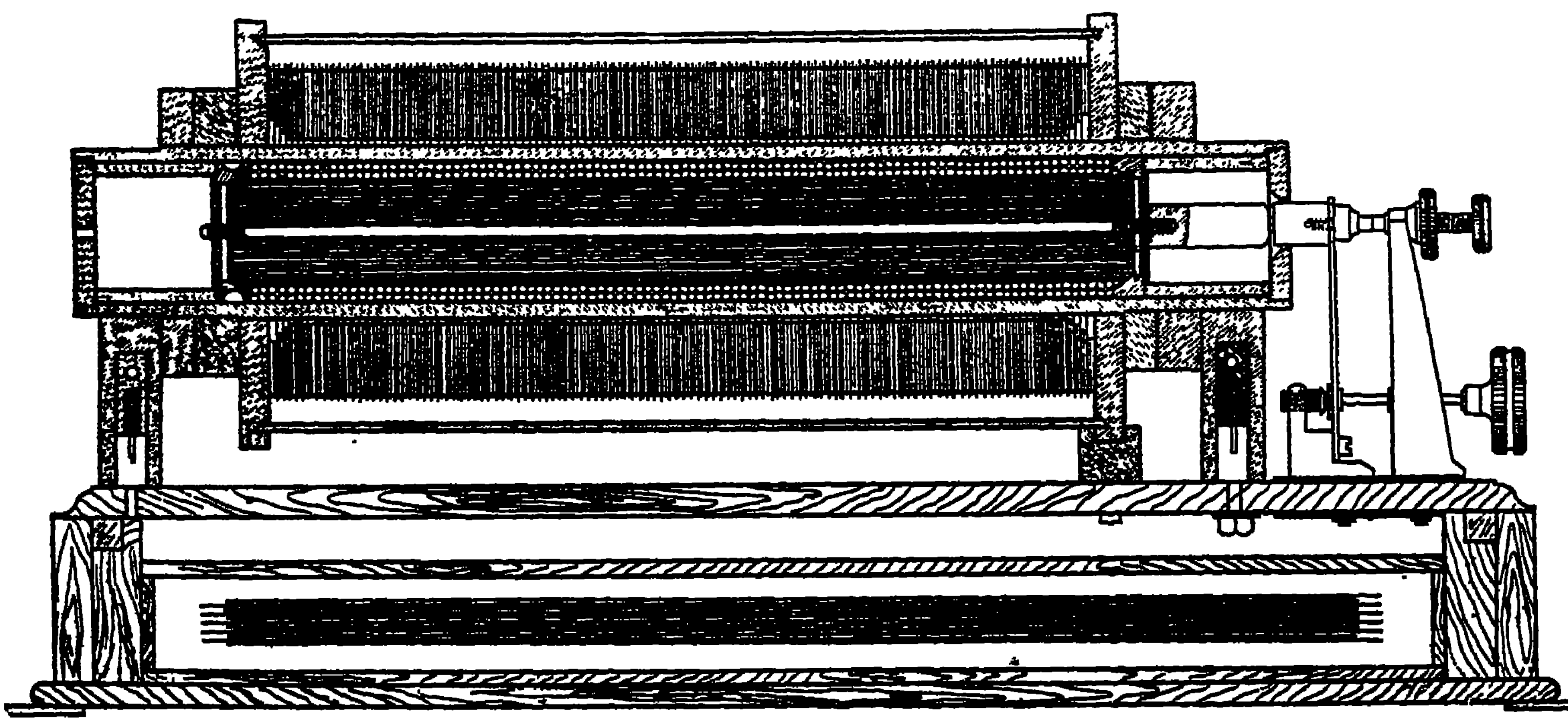


FIG. 192B.—Section of Induction Coil.

coiled upon an iron core. Page, to cause interruption, used in 1837, an interrupter consisting of a copper star dipping into mercury.

In the same year what was essentially the first induction coil was produced by Sturgeon, having both primary and secondary circuits with a " dipper " type break and intended for medical purposes.

The final evolution of this coil, to what is essentially the modern type of induction coil, appears to have been due independently to Page in America in 1850, and to Ruhmkorff in Germany in 1851, although it is stated Ruhmkorff had been occupied in such coil development since 1843.

The addition of the capacity across the primary break was due to the celebrated physicist Fizeau in 1853.

Such early coils did not have a modern sectionally wound secondary

circuit. This is again apparently a simultaneous improvement, since although the Brights in 1852 and Poggendorf in 1854, constructed such sectional coils, a similar coil appears to have been exhibited by Siemens at the London Exhibition of 1851. From this date further coil development appears to have been chiefly in the construction of monster coils. That made by Apps for Spottiswood, in 1886, and those of Klinglefuss at a later period, deserve particular mention. To Apps is due the well-known hammer break, and to Klinglefuss, is due the attempt to render the induction coil more efficient by giving it a nearly totally enclosed magnetic circuit, as in the case of the alternating current transformer.

Rochefort and Wydts, in 1897, produced coils in which another feature of transformer practice was utilised, namely the immersion of the coils within a semi-liquid insulating wax medium.

Wehnelt in 1899 produced his well-known electrolytic break, subsequently modified by Caldwell, Simon and Newmann.

The theoretical treatment of induction coil action is largely scattered, and, whilst many constructional books have been produced of a popular type, this instrument has not received serious treatment as is the case with the analogous alternating current transformer.

Of the original papers, that of Colley in 1891 deserves first mention, as well as the treatment of coupled magnetic circuits (as in the induction coil) by Overbeck in 1897. Mazuno in 1898 first studied carefully the effect of primary capacity upon the coil action. Rayleigh in 1901 further developed the mathematical treatment and so showed that, if the primary circuit of the coil could be sufficiently rapidly interrupted, the action of the primary condenser would be negligible or adverse in its action. This theory he put to test by interrupting the primary circuit by a rifle bullet, and obtained results consistent with his theoretical results. More recently the theoretical aspects of the induction coil has received still more complete mathematical treatment by Taylor-Jones, whose book is undoubtedly the most serious treatise yet written. Taylor-Jones showed, contrary to Rayleigh, that with rapid break of the primary circuit, the primary circuit should affect the coil's action and, repeating the Rayleigh rifle-bullet experiment, obtained results contrary to Rayleigh.

Crowther * has suggested that these differences are to be explained by differences of coil construction, that of Rayleigh being a non-oscillatory close-coupled transformer and that of Taylor-Jones an oscillatory loosely-coupled oscillation transformer, an explanation doubtless correct.

Of the text-books upon induction coils, worthy of notice is that of Lewis Wright † in 1897, which was the first important treatment and incidentally contains considerable information upon early X-ray tubes

* *Brit. Jour. Rad.*, 21, p. 59, 1925.
† L. Wright, "The Induction Coil in Practical Work" (Macmillan).

and X-ray excitation. Rühmer * in 1904 published a book very similar in its scope, but prior to the work of Taylor-Jones, the most serious book is that of Armagnat † who made tentative attempts towards theoretical design. Codd ‡ has written a book which is comprehensive as regards, but limited to, practical construction of coils, the only theoretical treatment consisting of the illustration of oscillograph curves under varying conditions.

The actual construction of coils, developed in the hands of Apps, Spottiswood, Siemens, Klinglefuss, Rochefort and Wydt, may be considered to have reached its zenith prior to the discovery of X-radiation by Röntgen in 1895. Other than for philosophical experiments, no practical use of any magnitude has been made of the induction coil, although early experiments of Lenoir in 1860, using the coil to ignite gas engines, foreshadowed the development of very small coils for ignition purposes now largely superseded by magnetos.

The more convenient use of alternating energy and transformers would doubtless have resulted in the induction coil falling into oblivion but for the development of wireless telegraphy, from Hertz's early experiments, by Lodge and Marconi and the discovery by Röntgen of X-radiation. For the production of the low-energy values of electrical energy at high potentials necessary at this period for both these purposes, the induction coil was very suitable and all early wireless and X-ray apparatus was coil-operated.

This resulted in coil manufacture for X-ray purposes being placed upon a sound constructional basis, particularly by Newton and Wright, Dean and Butt in England, Siemens and Reiniger, Gebbert and Schall in Germany, Drault, Gaiffe and Robinquet in France.

In the region of wireless telegraphy, the need of greater range and power early resulted in the replacement of the induction coil by the alternator and high-tension transformer capable of giving greater outputs, and the induction coil was relegated to small emergency sets, and is, even in this field, being replaced by methods of excitation by thermionic valves.

In the X-ray field the induction coil has held sway much longer as, despite the use of transformers for X-ray tube excitation by Koch in Germany, and Snook in America, and although this method was early utilised by Siemens and Halske, and notwithstanding the greater output of radiation which could so be obtained, the induction coil was, until the end of the late war, still the chief method of producing high-tension energy for X-ray purposes in England, and much of the English Army apparatus was of coil type until the American Army, utilising transformer apparatus, showed the greater possibilities and power of the transformer, first manufactured in England by Newton and Wright in 1907.

* E. Rühmer, "Konstruktion, Bau und Betrieb von Funkeninduktoren."
† "La bobine d'Induction" (Gauthier-Villars, 1905).
‡ M. A. Codd, "Induction Coil Design" (Spon, 1920).

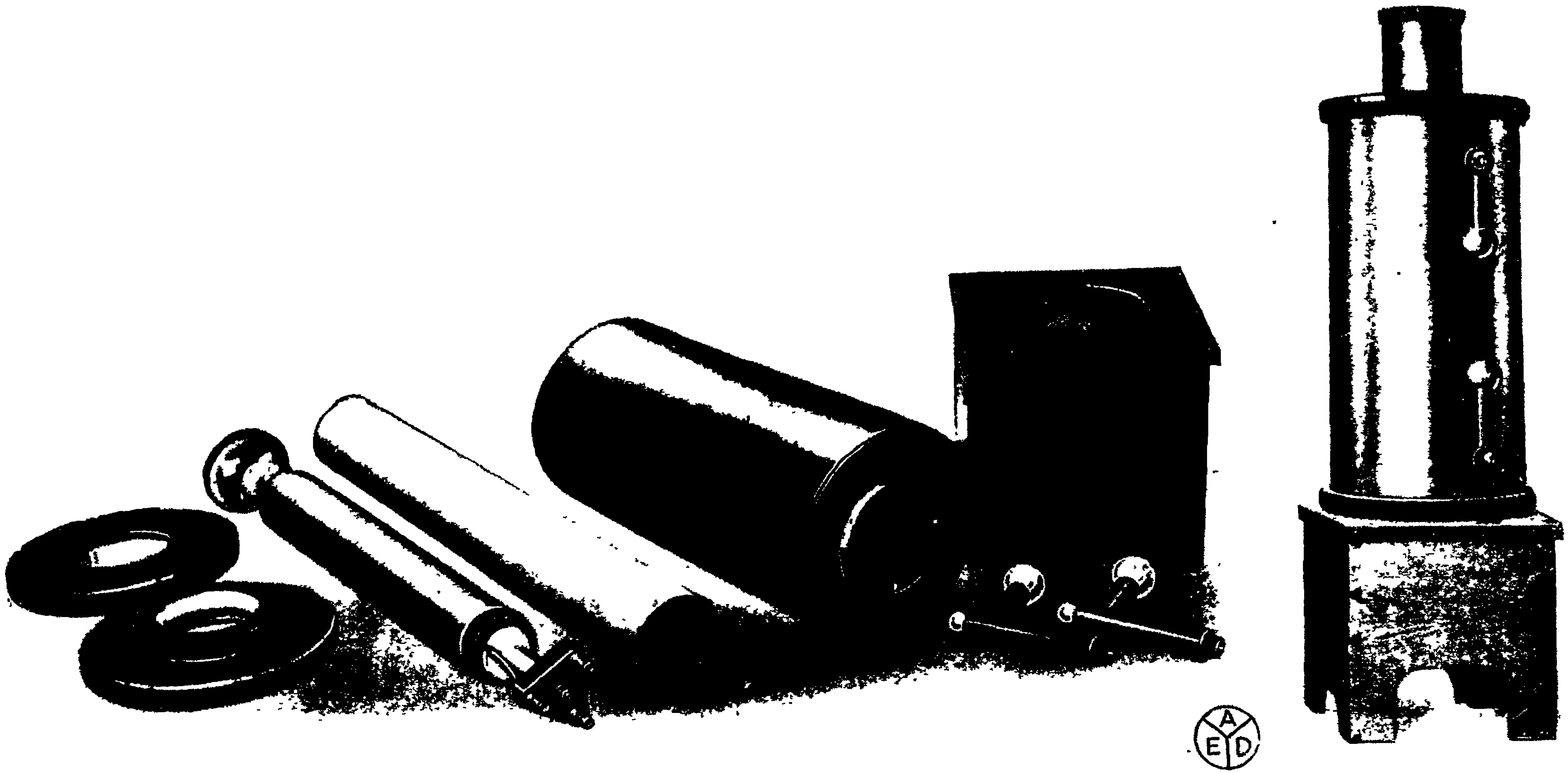
To resist its displacement in England were the high technical perfection reached by English coils and our native conservatism. As with the gas tube, many claims were made for the superiority of the induction coil type of discharge over the rectified transformer discharge, and, for these claims, there was little warrant on theoretical grounds.

There is no question that the induction coil, of very low efficiency (30 to 60 per cent.), cannot compare with the transformer of high efficiency (95 per cent. and upwards), for the production of high-tension energy, and, whereas a coil output is usually limited to 1 or 2 kw., there is no limitation to the transformer output, although custom and the limitations of the present X-ray tube retain this in the neighbourhood of 6 to 10 kw. Combined with the low efficiency, there are the great variations in coil action, dependent upon the vagarities of breaks of all types, undesired effects not present with transformers.

Whilst much has been claimed for the form of the voltage curve of the induction coil there are no theoretical reasons why this should have advantages over a truly equivalent sine wave voltage curve. Admitting any advantage of voltage curve form, such curve form can be equally imitated by a transformer, with the advantage of more regular discharge (p. 201, Vol. I.). Whereas such transformers have been commercially produced in Germany, their use does not appear to have become very general. Since the late war the transformer has more and more replaced the induction coil in the larger hospitals, etc., and the induction coil only retains its previous popularity for small installations where only an irregular and small amount of X-ray work is carried on. Even in the field of small portable apparatus the coil is more and more becoming displaced by the more convenient and regular transformer, with self-rectifying thermionic tube. When this type of tube becomes cheaper the use of induction coils for portable or small apparatus will doubtless no longer occur, and the coil will be relegated to history, as in the case of the once-favoured Wimhurst machine, which likewise failed, owing to the small energy values which could be obtained.

Although England and France were perhaps its last strongholds, where the question of expense does not limit its application, one may say that invariably all new radiographic installations are of the transformer type.

The ground of debate has therefore changed from the field of radiographic apparatus, for which field it was usual to attribute particular advantages for the induction coil, usually incapable of direct test, to the field of radiotherapy, where special virtues are still claimed for the induction coil discharge. In this connection one can only say that three out of four of the largest German firms use transformers, the American firms invariably use transformers for therapy work and the French apparatus is mixed. It appears therefore that it is only a matter of time



(1) End cheeks. (2) Core and primary winding. (3) Primary tube. (4) Secondary winding. (5) Stand. (6) High-tension terminals.

FIG. 193.—Components of Induction Coil (A. E. Dean).

[To face p. 253.

when the empirically designed and inefficient open core transformer, or induction coil, is entirely replaced by the more scientifically designed, easily controlled and efficient closed core transformer.

The question of transformer *versus* induction coil is more closely considered elsewhere.

The construction of the smaller type of induction coil is shown in Fig. 192B, which is an Admiralty coil with hammer interruptor.

We have centrally a core (Fig. 193), which in the older coils was a bundle of soft iron wires and in the modern coils is, as in the transformer, stalloy laminations of superior magnetic properties. Through the centre of this core is, with the hammer-break type of core, an iron rod to carry the magnet of the hammer break. As separate interruptors are invariably used for radiological purposes, this iron rod is often not present in radio-

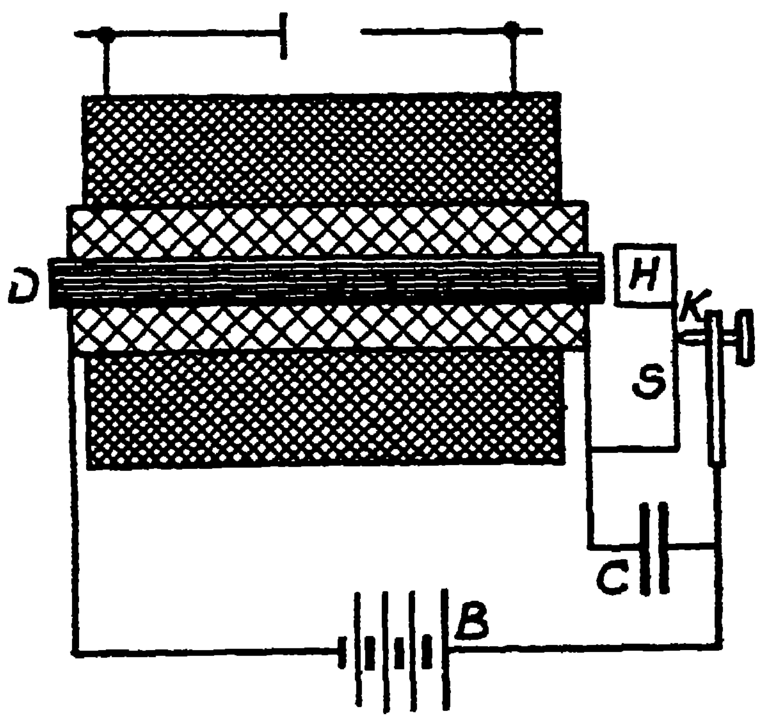



FIG. 194.—Diagrammatic Induction Coil.

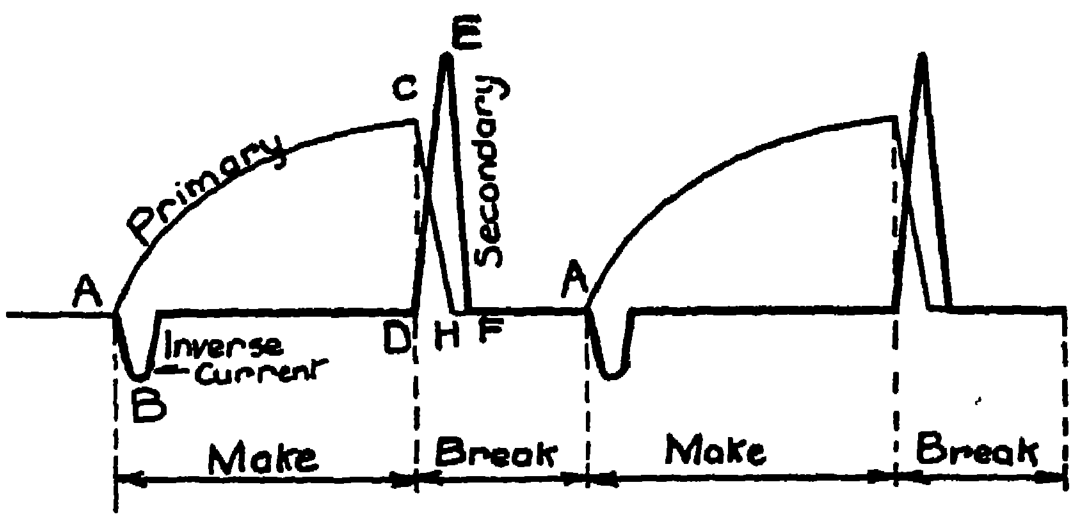



FIG. 195.—Action of Induction Coil. The scale of secondary voltage is very small in proportion to primary voltage.

logical induction coil cores, although sometimes inserted for purposes of rigidity.

This core, as in the transformer, is surrounded by a stoutly wound primary circuit, in turn surrounded by a stout insulating cylinder, upon which the secondary circuit of many turns of thin wire are wound—in the example shown in Fig. 192B wound in flat insulated sections

The open core transformer so formed is mounted upon a wooden stand in the base of which it is usual to insert a fairly large condenser. The hammer break, for convenience in adjustment, is invariably on the right in the smaller type of coil of Fig. 192B.

The action of the coil can be best considered in relation to Fig. 194. The hammer H is set to make contact and complete the primary circuit, consisting of a source of low-tension energy B, the primary winding and the contact of the hammer break.

The flow of current, which now occurs in the primary circuit, magnetises the soft iron core D, the flux in which gradually grows as in-

dicated by Fig. 195, where C is the maximum flux which can be obtained with the given current and given number of primary turns. This maximum flux should be on the sloping portion of the B/H curve (Vol. I.) of the core material and should not reach the flat saturated portion of this curve.

The growth of this flux must, by the Lenz law of magnetic induction, induce a voltage in the secondary circuit. As this magnetic growth is a comparatively slow growth and since the induced voltage is equal to the rate of change of lines of magnetic flux, the induced voltage in the secondary circuit is relatively small. It is this slow growth of secondary voltage AB which we know as " inverse " voltage and corresponding current, the current resulting from the establishment of the inverse voltage. One of the principal factors in induction coil design, is to make this growth of inverse voltage in the secondary as small as possible, so that its undesired effects are small, although we can never entirely eliminate it, it being a necessary phenomenon, in spite of the claims of some induction coil makers that all the " inverse current " is eliminated. The most which one is able to do is to make this growth so slow that the inverse voltage is so small that it is unable to drive any appreciable current *viâ* the average X-ray tube.

When the core has obtained the desired degree of magnetisation the iron armature H is attracted to the core by a force which is proportional to the square of the magnetic induction. This attraction increases rapidly and, as a consequence, the armature is drawn to the core magnet and interrupts the primary circuits *viâ* the interruptor contacts K and S. This results in a rapid decline of core magnetism which, being surrounded by a very large number of turns (60,000 to 100,000 or more) of secondary wire, induces in these turns a very high voltage DEF (Fig. 195).

A very high potential difference therefore occurs at the secondary terminals, sufficient to cause a spark of great length, or to drive a current *viâ* the highly exhausted X-ray tube.

As the primary circuit is interrupted the magnetisation of the core must necessarily decline and does so, to such a value, that the hammer is no longer attracted, when its spring control causes it to fly back to the resting position, until, the secondary discharge having ceased, the primary circuit is again completed and, as a result, the core is remagnetised and the cycle repeated.

As in the transformer of normal type, the primary circuit of few turns, carries a comparatively heavy current at low voltage, whereas the secondary circuit carries a small current (milliamperes) at high voltage. Neglecting losses due to resistance, chiefly in the high-resistance secondary, we may approximately write $E_1C_1 = E_2C_2$, as for the transformer.

The decline of the current in the secondary, after its establishment, passage, and loss of energy by sparking, electrical radiation, and other

causes, must cause a variation of core flux. As a result a potential difference must be induced in the primary circuit. As this potential is due to the rapid rate of change of flux in the core, a comparatively high voltage is induced in the primary, which may be very much greater than the original primary voltage. In consequence there is a great tendency for a spark, or a continuous spark or arc, to form over the interruptor contacts of the primary circuit.

To prevent this a condenser C (Fig. 194) is shunted across the hammer break contacts, which stores up this energy electrostatically. As time is required for this storing of energy, the tendency to sparking across the contacts S and K is so obviated.

In practice the actual phenomenon is not a simple discharge of the energy of the secondary circuit, but we have a highly damped oscillatory discharge in which the energy of the secondary circuit is returned to the primary, which in turn returns it to the secondary, energy so oscillating between the two circuits until the resistance losses decrease its value to zero.

Similarly the discharge *viâ* the contacts is not a unidirectional discharge but an oscillatory discharge, which, owing to the high resistance of the circuits, is rapidly damped out. As these oscillations will, in one direction, be dependent upon the continuity of the primary circuit, the desired unidirectional discharge will be more nearly attained the less the primary circuit is completed by arcing *viâ* the hammer interruptor contacts, and is therefore dependent upon the efficient action of the condenser. If the primary circuit can be so rapidly broken and the distant ends so rapidly removed from each other, for example by a rifle bullet, the discharge may be unidirectional, since the primary circuit cannot again be established. As a consequence the condenser is then unnecessary and without effect. With the Wehnelt type of break, which tends to this type of instantaneous interruption, the condenser is dispensed with.

Imposed upon all induction coil discharges we have electrical oscillations, as the secondary circuit possesses capacity, by virtue of its sectional windings, which, for the high-frequency oscillations, transfer energy electrostatically *viâ* the insulation, rather than electromagnetically *viâ* the conductor. As a result the risk of breakdown of insulation is greatly increased above the risk for a unidirectional current discharge.

Whilst the study of these oscillations is a highly technical mathematical one, the, design of induction coils is largely empirical. In fact, the production of good induction coils is usually entirely empirical and depends more upon the equally important qualities of good and careful workmanship, the careful selection of good material particularly for insulation, and the avoidance of faulty and careless winding.

We may similarly, to the transformer, consider the induction coil consecutively as regards the core, primary circuit, secondary circuit, and insulation.

## THE CORE

The whole difficulty of the theoretical consideration of the induction coil lies in its open core.

If we consider this in terms of the magnetic circuit, as the iron path is small in relation to the air path and, as we have no means of ascertaining the actual air path, it is impossible to perform any design calculations except in the case of the practically closed core induction coil of Klinglefuss, described later.

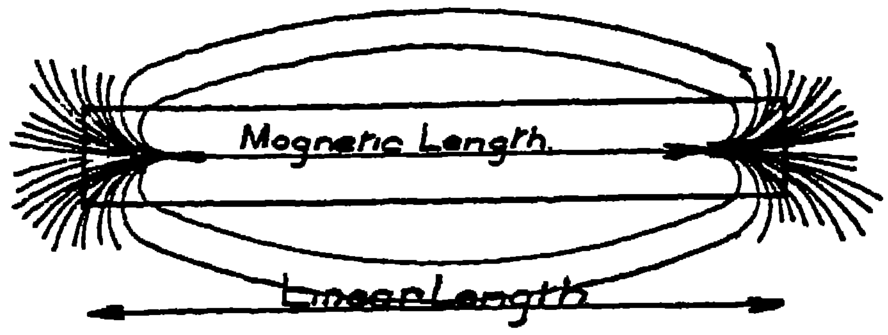


FIG. 196.

Whereas a closed core has no free pole surface, with the open core, the free pole surfaces tend to prevent the establishment of further lines of flux and to produce a demagnetising effect. This is known as the coefficient of demagnetisation N (see Vol. I.) which is related to the magnetising field H′ as $H = H' - NI$, where H is the effective magnetic field and I the intensity of magnetisation.

Maxwell and others have computed the demagnetisation factor for the case of a magnetic ellipsoid. It is customary to approximate a long

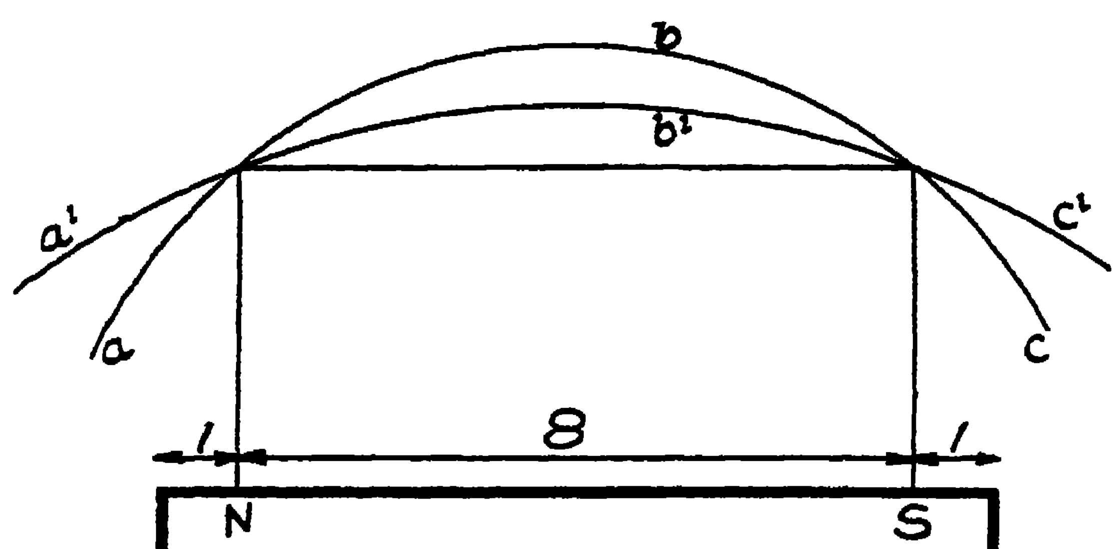


FIG. 197.—The Upper Curved Lines, by their Height above the Core NS, represent Comparative Induced Voltages at Various Distances along the Core.

straight solenoid to such ellipsoids. Such approximations are of no practical interest in design since, whilst it is of theoretical interest to know that the demagnetisation factor is about 6 per cent. for a solenoid whose ratio of $\frac{\text{length}}{\text{breadth}}$ is 200, as in practice we deal with ratios of from 6 to 15, for which the above approximation no longer holds, such theoretical conceptions are valueless.

Particularly is this the case since we see that, as I, the intensity of magnetisation, will vary with the degree of magnetisation so the subtracted component will necessarily vary and so, for the same material

and the same dimensions of core, the effective field will vary with the magnetising force, *i.e.*, with the primary circuit current.

It is here the engineer steps in and directly measures the actual magnetic value of a core under the given conditions of practice.

It is well known, and easily demonstrated with iron filings, that the magnetic length of a magnetic solenoid does not correspond with the actual physical length (Fig. 196), owing to the demagnetising properties of the free surfaces.

It is therefore uneconomical to wind these ends with a large number of expensive windings of secondary and, as a preliminary, it is necessary to determine what we may consider the effective magnetic length of an induction coil core.

This is determined experimentally by an exploring coil and ballistic galvanometer, with which comparative or absolute measurements are taken for various positions along the long axis of the core, when excited by a primary winding. As a result it is found the value of ballistic galvanometer readings varies with position, as shown by the heights of the curved lines in Fig. 197, this being a measure of N, the number of lines of force cutting the exploring coil.

The actual values will depend upon the area of the exploring coil, since N = area, times average flux density, but whilst these values may differ widely, as shown at the centre of the core, as the ends are approached they tend to run together, incidentally showing that at the ends, owing to straying of the magnetic lines, the field of magnetic force falls off rapidly with the distance from the core.

Results of such tests indicate that it is only economical to wind about 80 per cent. of the actual magnetic length, so that, if $d$ is the actual magnetic length, the effective length may be considered as decreased by the diameter to give the distance between the magnetic poles, and only 80 per cent. of this is to be wound with the primary and secondary, *i.e.*, the secondary length equals $0{\cdot}8(l - d)$, where $l$ and $d$ are actual length and diameter.

The primary winding does not pass to the actual ends of the core as it would mechanically be liable to slip off, but to continue the core too far beyond the winding would tend to increase the high-resistance air path.

We have next to determine the general size of the core and here, as in the transformer, where we used the expression $D = 2{\cdot}25 \times \sqrt[4]{\text{kv.a.}}$, so we use an empirical relation of "15 lb. of iron for every kilowatt of primary energy, *i.e.*, product of volts and amperes."

For any case we shall be given in the specification ;—

(1) Voltage of supply for primary.

(2) Desired maximum spark length, which is equivalent to a knowledge of approximate secondary voltage.

(3) Desired secondary current.

To determine the primary energy we may connect the unknown current by the relation ;

$$V_{\text{primary}} \times C_{\text{primary}} = V_{\text{secondary}} \times C_{\text{secondary}},$$

in which all the factors are known except C, it being assumed that the secondary current does not lag behind the secondary voltage. This, because of the highly inductive secondary winding, is far from the case.

We combine this discrepancy with the further unknown error of low efficiency of the induction coil, due to the demagnetisation and open air path of the magnetic flux, by assuming, again on empirical and experimental grounds, an efficiency varying from 30 per cent. to 60 per cent., both values comparing very unfavourably with the usual 95 per cent. transformer efficiency.

If we wish to ensure the desired secondary voltage and current we shall assume only a 30 per cent. efficiency. If commercial considerations come into consideration and the core is long and more effective magnetically we may assume the larger efficiency.

The primary current $C_p$ required is therefore obtained from the relation ;—

$$C_p = \frac{100}{30} \times \frac{\text{secondary voltage} \times \text{secondary current}}{\text{primary voltage}}$$

the lower efficiency being selected for safety.

Knowing primary voltage and current, the input watts are determined and weight of core calculated as above, *i.e.*,

$$\text{Weight of iron} = \text{kilowatts} \times 15.$$

Having determined the weight of iron for the core this volume may be distributed in an indefinite number of ways varying as ;—

(1) Very short length as compared to breadth. This will result in a very large demagnetising effect and short winding length for both primary and secondary, the latter of which must have the outer coils far from the central intense magnetic field and be inefficient.

(2) Very large ratio of length to diameter. This will tend to decrease the demagnetising effect and allow a large number of primary and secondary coils to be closely and efficiently applied to the core. On the other hand, if this view is pushed too far, the area becomes small, so that the flux density for a large number of primary turns becomes great, and tends towards undesired saturation, *i.e.*, above a value of 80,000 lines per square inch. Also, for many purposes, the space for a long induction coil is not available.

There is hence some intermediate value, where these opposing conditions give the most advantage. This can only be decided by trial with

differently proportioned cores. It is therefore necessary to plot the relation of induction per unit area, to the ampere turns, *i.e.*, product of amperes C in primary windings and turns N per unit length, against the ratio of $\frac{\text{length}}{\text{diameter}}$ of the core.

It is immaterial as to the units employed, for example, we may plot

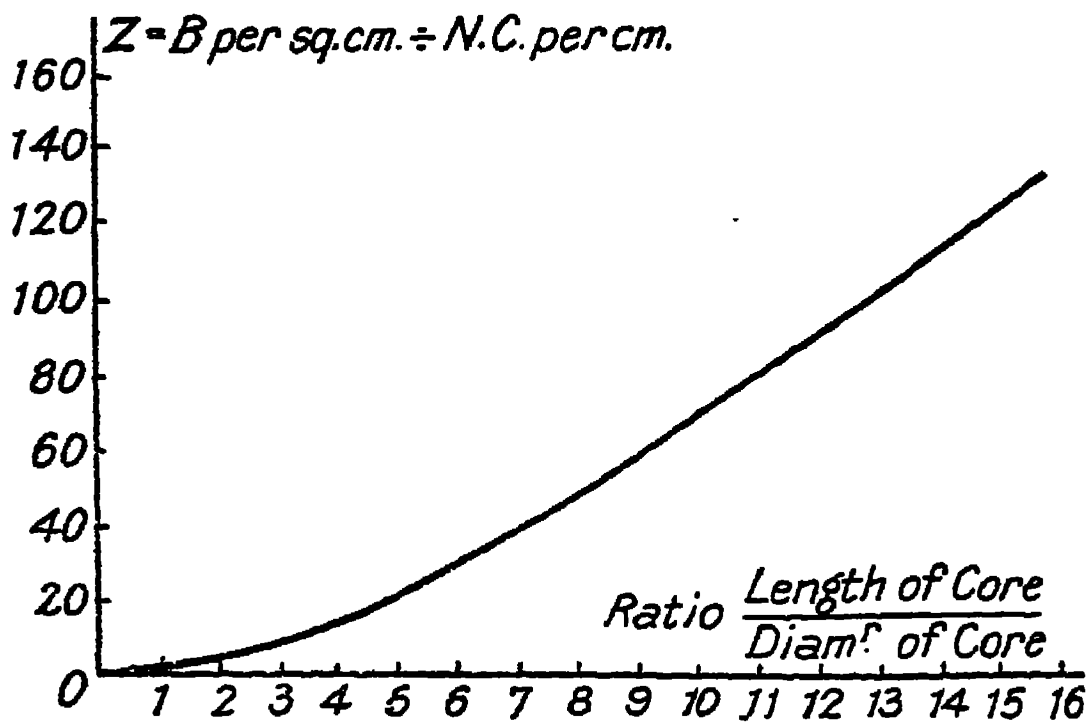



FIG. 198.

$\frac{\text{induction per square inch}}{\text{ampere turns per inch,}}$ (a value to which we follow Codd in giving the symbol Z) or we may plot $\frac{\text{induction per square centimetre}}{\text{ampere turns per centimetre}}$, in which case, calling the former $Z'$, we have the numerical relation $Z' = 2{\cdot}54\ Z$.

If values of Z and $\frac{L}{D}$ are plotted it is found the resulting curve (Fig. 198) is first curved and then at a value of Z about 25 and of $\frac{L}{D}$ about 6 the curve takes on a straight-line course which it continues to values beyond $Z = 160$ and $\frac{L}{D} = 16$.

The lower value is most suitable when a large current at a low voltage is desired, the later value when high voltage and small current is desired, the variation being dependent upon the relative number of lines of induction enclosed in each area.

Codd recommends for average values, a ratio $\frac{L}{D}$ of 10 to 12, a value which is generally selected for X-ray work, although power induction coils, such as those used for wireless transmission have values of about 8.*

* d'Armagnat deduces upon approximate theoretical grounds a ratio $\frac{L}{D}$ of 10 ("La bobine d'Induction," p. 55).

Knowing this ratio, it is now only a matter of arithmetic, the density $\delta$ of the core iron in pounds per cubic inch being given, to work out the size of core since $\left(\pi\frac{D}{2}\right)^2 \times L \times \delta =$ kilowatts $\times$ 15.

The older cores were of soft annealed iron and special methods of annealing were used. The event of the highly magnetic silicon alloys of iron, such as stalloy, specially prepared for their magnetic qualities and insulined with paper to prevent eddy currents, has practically replaced all the iron-wire cores in modern practice and the design now closely follows that of the stepped transformer core. The greater the number of steps, the more closely is the perfect circular form reached, but this is not entirely desirable as the resulting channels, with a lower number of steps, ensure better cooling. Many special advantages have been claimed for wire, as compared to laminations, mostly based upon conservatism to change. Had stalloy laminations been available for the earlier coils, there is no doubt soft iron wire would never have been used. This is produced for a variety of purposes of which the magnetic use is comparatively unimportant, and is, in consequence, not likely to be as efficient as laminated transformer iron particularly produced, after extensive tests, to enhance its magnetic properties, for a single purpose only. Laminations also " age " better than wire cores which are more liable to deep oxidation as time goes on. For this reason, the wire core is often soaked in melted paraffin wax before winding the primary. If the coil is intended for use with the hammer type of interrupter, a central rod, to carry the hammer magnet, is inserted. For X-ray purposes this is rarely necessary unless some form of magnetic break (*q.v.*) is to be used. The sheet stalloy type of core, as compared to the iron-wire type, allows a greater area of iron to be introduced and, for this reason is preferable, as it decreases the flux density and iron losses. The thickness of lamination is chosen on the same principles as for the transformer, with regard to frequency of interruption. Similarly the core is assembled and taped with several layers of insulating cloth such as Empire cloth.

The use of compressed cores of magnetic materials, for example, iron filings in colophony resin, in order to overcome eddy current effects has been suggested.*

Before leaving the core we may conveniently mention various exceptional coils. For " single flash " coils, usually a misnomer, it is desired to magnetise slowly the core to large values of total flux and then to interrupt the primary circuit rapidly, to give a very rapid fall of magnetism.

As this will be the product of induction B ($= \mu$H) and area A, it is of advantage to employ a core of much larger area than that described, which is intended for more average work, where it is inadvisable to have

* Brit. Patent 239,787/1925.

too great a total induction value, which increases the lag of the growth and decline of magnetism, when the current is made and broken.

It has often been attempted to increase the exceedingly bad efficiency of the induction coil, due to its open core construction, by giving it a closed construction, a method used by Klinglefuss as long ago as 1901.

It is impossible to use a totally closed core as in the transformer, where the conditions of operation are entirely different.

In the transformer when the core is magnetised in one direction, the resultant change in direction of the alternating current itself demagnetises the core, prior to its remagnetisation in the reverse direction. In the induction coil, on the other hand, the only demagnetising action is due to the high magnetic resistance of the large air path when the magnetic-motive force (due to the primary current) is removed. If the circuit is completely closed, this high resistance of the air path is absent and the core is unable to demagnetise sufficiently rapidly, so that the subsequent

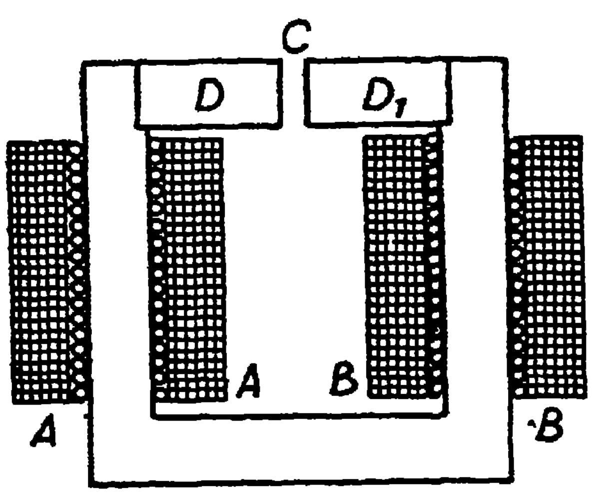



FIG. 199.

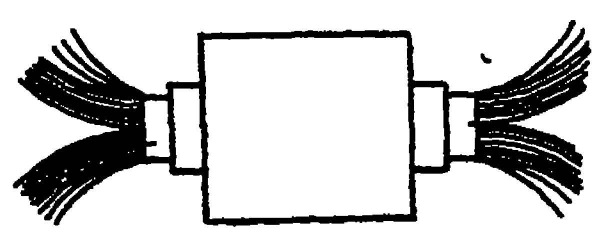


FIG. 200.

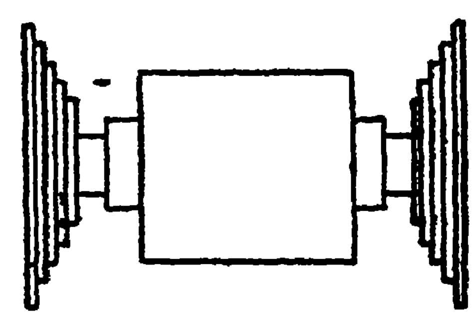


FIG. 201.

" make " period finds the core still practically magnetised and the resultant change of flux and induced secondary voltage is negligible.

To avoid this Klinglefuss used a duplex core of the form shown in Fig. 199, having a small air gap C of large area. The ratio of the permeabilities of iron and air, being in the neighbourhood of over 2,000 to 1, this small air gap, as soon as the primary circuit magneto-motive force is removed, offers an enormous resistance as compared to the iron and is sufficient rapidly to demagnetise the core (see Chapter III., Vol. I.).

On the other hand, whilst during magnetisation, this gap also offers a great resistance to the establishment of the field, this resistance is negligible compared to the large air path of the normal coil, which is many times that of the iron path. The nearly closed construction prevents the straying of the lines of force over a large area of air, as compared to the open core construction, and so improves the efficiency.

Klinglefuss in his paper,* gives the result of these modifications in terms of the increase in voltage with the closed core, as compared to the voltage (in terms of spark length) with the same number of secondary turns, on the same area of core, with the open core construction. This

* Klinglefuss, *Annalen der Physik.*, 5, p. 837, 1901.

superiority increased rapidly with increase of secondary voltage, as may be appreciated from the following figures given:

| | | *Secondary Turns.* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 6,000 | 8,000 | 10,000 | 12,000 | 14,000 | 16,000 | 18,000 | 20,000 |
| Spark Length. Centimetres | Open core | 6 | 8½ | 11 | 13½ | 16 | 18½ | 21 | 23½ |
| | Closed core | 7½ | 12½ | 17½ | 22½ | 27½ | 32½ | 37½ | 42½ |

It should be further mentioned Klinglefuss used for his coils laminated Swedish steel of 0·5 mm. thickness and also oil immersion for the coils. He showed that, whilst with oil immersion a 45-cm. spark could be obtained, with the same coil when not immersed only a 35-cm. spark could be obtained. For sheet laminations he used a $\frac{L}{D}$ ratio of 20 : 1 as compared to a ratio of $\frac{L}{D}$ of 12 : 1 for a wire core.

Klinglefuss' paper, prior to X-ray work, is very interesting since it antedates the so-called modern "duplex coil" with oil immersion. Codd has claimed to have originated this during the period of the late War, prior to Reiniger, Gebbert and Schall's "symmetry apparatus." It is evident Klinglefuss has the greatest claim to the priority of this innovation by decades.

Klinglefuss' coils were largely used in Germany and many of the older journals illustrate them. The objections to such "closed" core transformers are usually stated as ;—

(1) Practical difficulties in winding, as compared to the open core. Whilst this is granted, with cores and yokes, this is not very great and is done every day in transformer manufacture.

(2) Demagnetisation does not occur sufficiently rapidly during the break period. This is a question of proportioning of the iron and air paths, the latter being, in the open core construction, far more than is necessary and can be therefore very advantageously decreased, by the practically "closed" core construction with small, but sufficient, demagnetising air gaps.*

Other attempts in closing the core resulted in the use of "hedgehog" cores as used in the early Swinburne transformer. In these (Fig. 200) the iron core was splayed out at the ends (hence the name), so aiding the formation of a smaller air return magnetic circuit than is the case with the straight core.

* d'Armagnat ("La bobine d'Induction," p. 54) considers such a core and shows that if $\lambda$ is the length of the iron path and $\lambda'$ the length of the air path, then the energy is a maximum when $\frac{\lambda}{\lambda'}$ equals the permeability $\mu$ of the iron.

More recently * Dessauer has constructed coils (Fig. 201) with the core terminating in iron discs of 40 cm. maximum diameter, arranged in five steps of 0·5 mm. thick iron and has found considerable increases of current output, ranging from 215 per cent. downwards, for the same spark gap, or conversely, considerable increase in spark distance.

Dessauer particularly points out the application to "single flash" work.

## THE PRIMARY CIRCUIT

The determination of the primary winding is again largely empirical, the primary current and therefore permissible gauge of wire having already been determined.

Codd gives a formula for the number of primary turns as;

$$T = 10^4\sqrt{\frac{Ll}{ZA}}$$

where Z = the ratio Z′ already mentioned on p. 259.

T = total number of turns.

L = self inductance which Codd calculates from the alternating current value $E = 2\pi LC$, which, as the current is unidirectional, he modifies as $E = \pi LC$.

$l$ = turns per inch.

A = area in inches.

Codd has informed the present writer that this formula is purely empirical. It is remarkable that accepting certain questionable assumptions, this formula can be actually deduced from first principles.

Let the total induction of a core of area A and of permeability B be N in c.g.s. units.

Then $$N = BA$$

and since $$E = \frac{\text{change of induction}}{\text{change of time}} = \frac{dN}{dt}$$

When this rises in time $t$ to its value N, then;

$$E = \frac{BA}{t} \text{ per turn}$$

or, for T turns,

$$E = \frac{BA\,.\,T}{t\,.\,10^8},$$

the value $10^8$ being introduced to bring E in terms of volts ($10^8$ c.g.s. units = 1 volt). As in the case of the transformer, we must introduce a form factor $f$. If we assume an exponential form of voltage variation across the ends of the primary, as occurs in practice, over a period of make two-thirds the total time of (make plus break) Duddell has shown this to be $f = 2$ (see Vol. I., Chapter V.).

* "Induction Coil Design," Dessauer, *Phys. Zeits.*, 22, p. 425, 1921.

Unlike the case of the transformer, the time of make and frequency $\eta$ relation $\frac{1}{t} = \eta$ does not hold, since $t$ is only two-thirds the complete time which equals $\frac{1}{\eta}$. Hence $t = \frac{2}{3}\eta$, and this is the actual rate at which the voltage grows. Hence;

$$E = \frac{BAT}{10^8} f \cdot \frac{3}{2}\eta,$$

but
$$B = \mu H,$$

hence;
$$E = \frac{\mu HA \cdot T \cdot f\frac{3}{2}\eta}{10^8},$$

but, following Codd,
$$\eta = \frac{E}{\pi LC},$$

whence:
$$E = \frac{\mu HATf\frac{3}{2}E}{10^8 \pi LC}$$

and since
$$Z = \frac{B}{nC} = \frac{\mu H}{nC}$$

$$10^8 \pi LC = \frac{ZnC}{H} \cdot H \cdot AT \cdot f\frac{3}{2}$$

Further
$$T = nl,$$

whence;
$$\pi C 10^8 = \frac{Z \cdot CA \cdot T \cdot f\frac{3}{2}}{l}$$

$$T^2 = \frac{10^8 \pi Ll}{ZAf\frac{3}{2}}$$

or
$$T = 10^4 \sqrt{\frac{Ll}{ZA} \cdot \frac{\pi}{2 \times 1 \cdot 5}}, \text{ since } f = 2$$

now $\pi = 3{\cdot}1$, and the fraction $\frac{\pi}{3}$ tends to unity whence;—

$$T = 10^4 \sqrt{\frac{Ll}{ZA}}$$

the empirical relation of Codd, except, whereas our units of length are centimetres he uses inches, a difference which is only numerical and is seen to cancel out, it being remembered that length appears in the constant Z.

Codd states this formula has been found satisfactory in practice and serves to fix T, the total number of turns. Since the magnetising field H is given by $4\pi nC$ c.g.s. units, it would at first appear that it would be most profitable, with the given current C, to make $n$ very large to produce a large value of H. Such a solenoid has however inductance which serves to oppose any rapid growth or decline of current, and so to

prevent a rapid interruption. We have shown (p. 111, Vol. I.), that the inductance of a solenoid of the type in question is $(4\pi n C) n l A \mu$, *i.e.*, proportional to $n^2$. If we follow the above reasoning, we should obtain such a large value of L, that a long period of magnetisation of make would be necessary. Codd's formula therefore serves to find the suitable mean value. It should however be mentioned that in the above and in Codd's empirically derived formula, L is used when actually, owing to the presence of the secondary winding, a mutual and not a self inductance is present.

For the primary winding we have now determined E, C and $n$, and it is theoretically only a matter of calculating the length of wire $l$ and permissible resistance since this is given by $R = \Sigma \frac{l}{\pi r^2}$, where $R = \frac{E}{C}$. In practice wire-makers' tables which determine the safe current-carrying capacity are referred to. It will be found the primary winding will require a No. 12 or 14 S.W.G. conductor with a current density of about 2,000 amperes per square inch.

These tables also give the average number of turns per unit length which can be accommodated, a further 10 per cent. being allowed for slackness in winding, etc.

Given the length of wound core, a No. 12 or 14 D.C.C. wire will allow about eight or nine turns per inch length respectively, and, $n$ being known, the number of layers is directly determined. The insulation between turns follows somewhat upon the lines of the transformer primary, already fully described. Very often no further reinforcement of primary insulation is used. It must however be remembered that the voltage to which the primary winding is subjected is not merely that of the primary supply. As the core is very slowly magnetised by the primary no great strain is applied to the insulation. When the core is magnetised and the secondary flux is great another state of affairs arises. The secondary discharge is very rapid and, as the secondary and primary circuits constitute a step-down transformer, the voltage induced in the primary, owing to the rapid discharge and change of current in the secondary, may be very many times the primary voltage. The primary insulation must be accordingly proportioned and in general should, owing to the peaked type of discharge, be greater than for a transformer of the same voltage and milliampere secondary output.

We can roughly compute this induced primary voltage, if the number of turns $n_1$ and $n_2$ of primary and secondary are known, and the secondary spark distance, which reference to tables (p. 164, Vol. II.) allows us to interpret in terms of voltage. The transformation ratio $\frac{E_1}{E_2} = \frac{n_1}{n_2}$ allows us to compute $E_1$. This will be found to perhaps amount to several thousand volts, whilst the primary voltage may be only 100 volts.

cheeks, which are extended well beyond the secondary circumference to prevent the direct passage of sparks.

With section winding the voltage between primary and secondary increases from section to section and, as the maximum voltage is exerted at the ends of the coil the primary tube must be very stout to withstand the maximum voltage. This results in all the secondary turns being

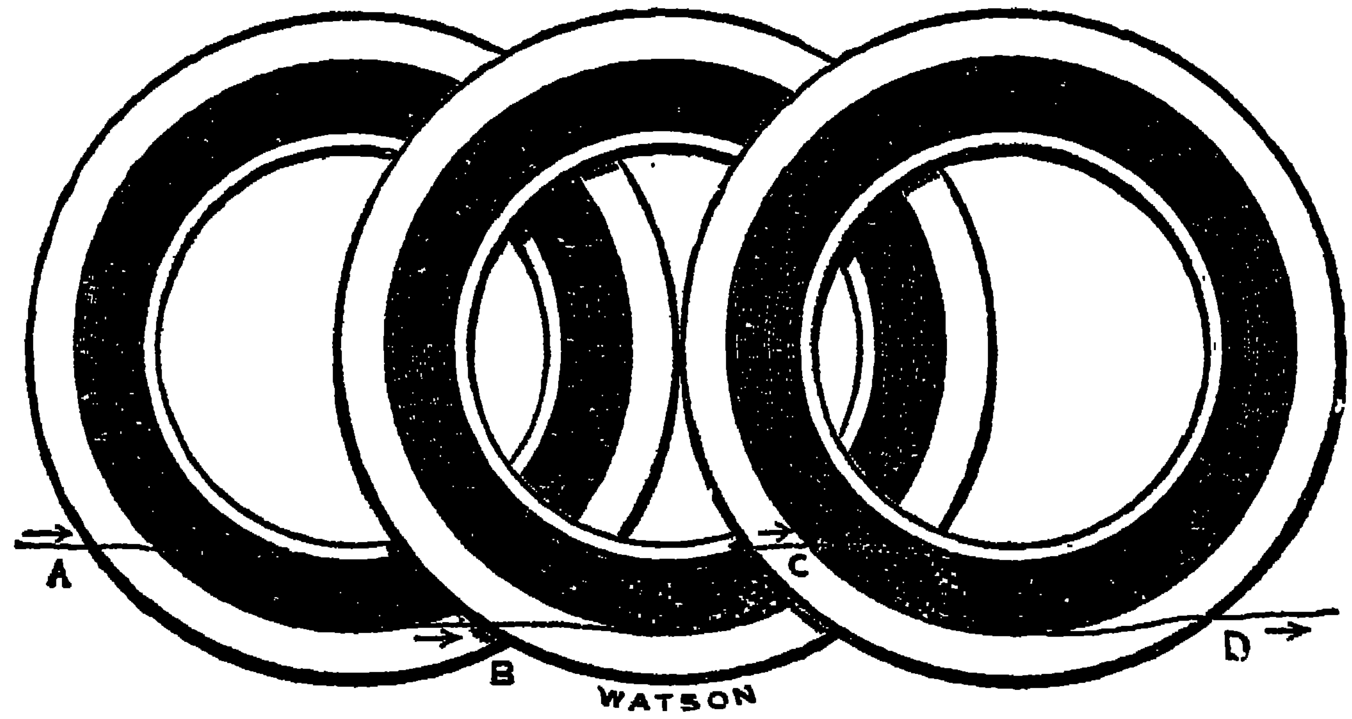



FIG. 204.—Miller Winding.

more distant from the core than with layer winding and the efficiency correspondingly suffers.

The section method of winding is taken to its limit in the method usually attributed to Miller, in which each section is only one layer of wire. Miller has ingeniously worked out the practical machine winding of such one-layer sections, so that the wire runs from section to section

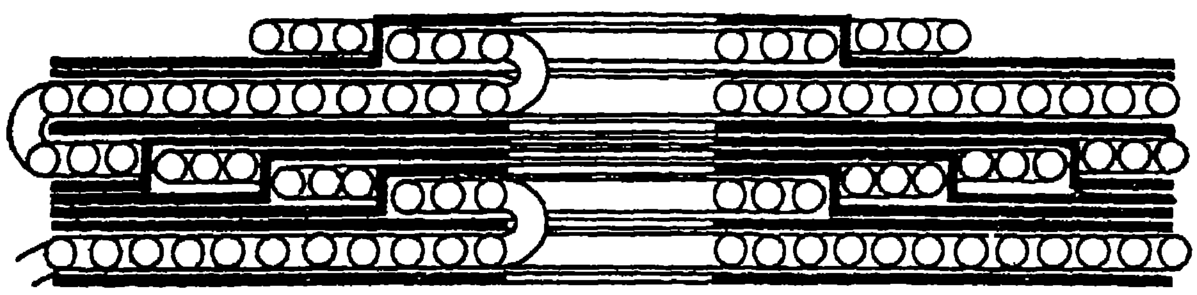


FIG. 205.—Klinglefuss Winding.

without a join (Fig. 204), the figure showing three such coils separated along their longitudinal axis. Each one-layer section is separated by a layer of paraffined paper and the connections are not from inner to outer, but change from inner to inner, outer to outer, so ensuring no connecting wire running across the windings of any section, with consequent risk of breakdown.

These sections may amount to a very large number (1,000 or more) and are finally heated to melt the superfluous wax and then all compressed together. By this winding the voltage difference between adjacent turns is reduced to a minimum.

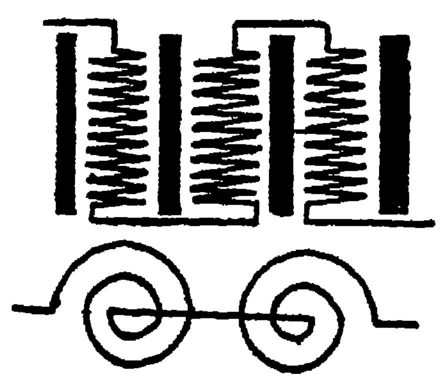
A similar method of winding was used many years ago by Klinglefuss in which the wire is wound in recessed ebonite or paper washers of graduated

dish form, the appearance of a section being as in Fig. 205. Whilst this method even exceeds the Miller method in separation of the windings and avoidance of high potĕntials between neighbouring windings, it is expensive, and tedious to wind. More disadvantageous is, that as with the Miller method, the larger part of the secondary volume is occupied by insulating material and not wire to increase the voltage. It is only necessary for very large coils such as those constructed by Klinglefuss.

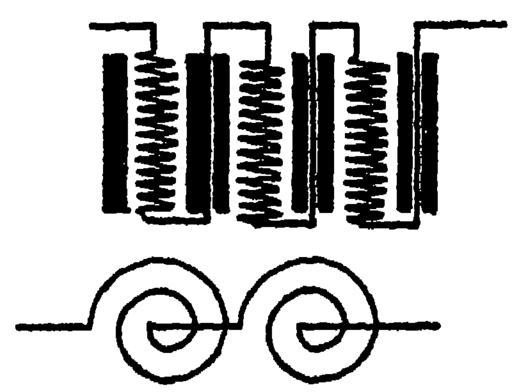
A less expensive method is to wind the secondary in multiple sections and then to encase these in boxes of insulating material, but this has little, if any, advantages over the more usual sections between ebonite cheeks.

In all multi-sectional windings of coils and transformers the direction of winding must be always the same or the magnetic field of oppositely wound single coils or sections would oppose each other and, whilst adding nothing to the voltage, would add to the resistance of the secondary.

This necessitates that each section is wound by a motion in the reverse



(a) Correct.



(b) Incorrect.

FIG. 206.

direction during manufacture by reversing the winding machine so that a direct connection can be made as in Fig. 206, *a*, so ensuring that a connection does not cross a whole coil as in Fig. 206, *b* which would necessitate further insulation between each coil and the lead.

An objection to the multi-sectional coil is that high-frequency surges are more easily produced, as the neighbouring coils act as condensers, with the intervening insulation as dielectric. They are therefore more apt to both give rise to high-frequency oscillations, whilst at the same time facilitating their passage in the coil. The layer winding has a smaller capacity effect in this relation.

For the details of coil and transformer winding practical text-books should be consulted. Practically all coils are now machine wound under the attention of an operator, who is able immediately to stop the machine to rectify any fault. A counter automatically counts the number of turns.

The wire usually passes through melted paraffin wax, before it reaches the winding machine and is wound hot and soft. When completed the secondary is heated under pressure, to drive off the air which may be in the windings and would cause brush discharge, or better, vacuum exhaustion is employed, as with the high-tension transformer (*q.v.*). It is then cast in a cylindrical block, with several inches of surrounding paraffin

wax, and is covered with a thin ebonite, but occasionally a porcelain cylinder, to prevent injury to the wax. The waxed secondary sections are then mounted upon the primary tube as shown in Fig. 207

## THE PRIMARY TUBE

As already mentioned, the objection of sectional winding is the need of a stouter insulating sleeve, between primary and secondary, which reduces the magnetic and general efficiency.

As at one end the maximum voltage is exerted and as the use of tapered tubes is hardly economically practicable, the insulation at the lower tension end is excessive. This fact is very liable to tend to the use of a thinner tube and a less factor of safety at the high-tension end. With the Miller winding, as the winding is not carried right to the inner periphery of the insulating washer (there being a risk of the inner coils slipping and so coming into contact with neighbouring wires and the primary tube), this distance is further increased by the intervening wax, but, conversely this wax helps to reduce the primary tube thickness.

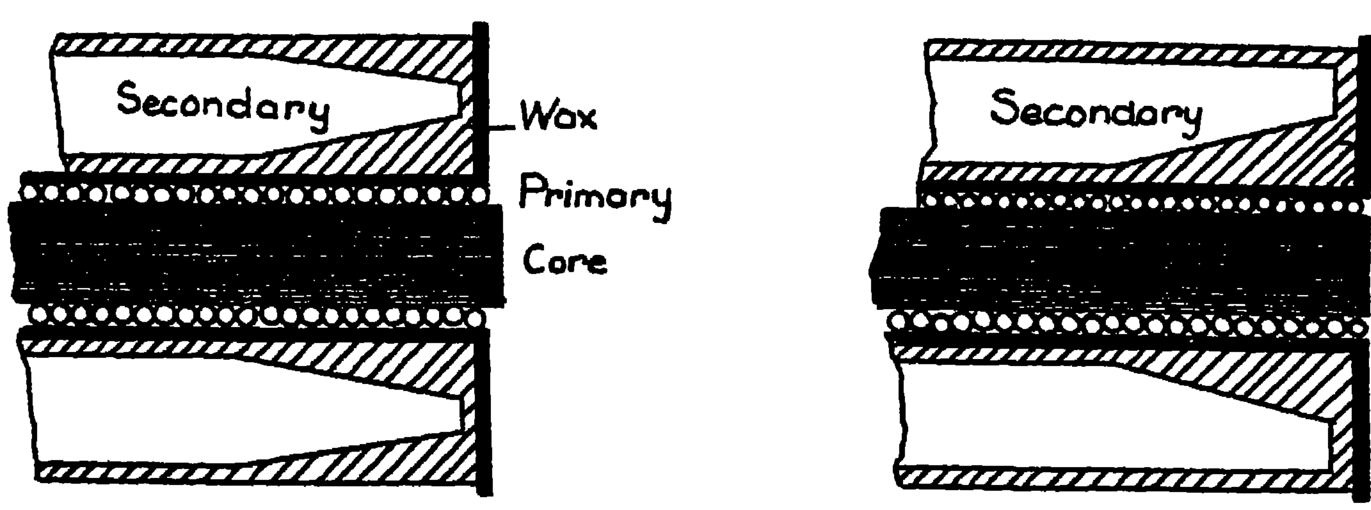



FIG. 208.—Tapered Secondary Coil Windings.

In some coils the secondary windings are tapered at the ends as shown in Fig. 208, with the object of increasing the distance between primary and secondary at the high potential ends and so, by intervening wax insulation, to prevent breakdown at this most dangerous region.

The primary tube is usually ebonite in the older coils and paxolin or micanite in the modern coils. Occasionally glass or porcelain is used.

A ¼ in. of micanite will usually withstand a voltage equal to a 16-in. gap for some minutes, and the thickness of the tube must be accordingly proportioned, with a suitable factor of safety. A ¼ in. is usually allowed for a 12-in. gap with a low factor of safety of 1·5. A greater factor of safety has the disadvantage of increasing the secondary to core distance. A 16-in. core would have a ½ in. thick tube, *i.e.*, a factor of safety of 2.

It is stated that, to avoid the effect of flaws this thickness is best made up of two ¼-in. tubes. This view is erroneous unless the coil is of the oil-immersed type, in which case solid and liquid insulation should be correctly proportioned in the manner indicated for the major trans-

G. 207.—Piling an Induction Coil Secondary (Messrs. Watsons).

[To face p. 272.

former insulation (p. 222). In a non-oil-immersed coil the use of two tubes introduces a very small air gap between the two component tubes. As a result, if the overall thickness is not great, the stress thrown on the small air gap will result in corona and eventual heating and breakdown of the insulation. A small clearance, with the intervening space filled by melted paraffin wax under pressure, would largely obviate this objection, but the total exclusion of air is difficult.

For the same reason, whilst it would facilitate repairs to have a secondary which easily slides upon the primary tube, this would also introduce air between the tube and secondary insulation. The waxed secondary is therefore usually melted upon the primary tube, except when vacuum exhaustion is employed.

Owing to the large difference of dielectric constant of glass or porcelain and wax, the use of these insulators is usually unsatisfactory and they are more liable to crack by local overheating.

The only method of avoidance of flaws in the preferable single tube is by direct test, prior to assembly of the coil, by the use of shaped flat electrodes across which a sufficiently high test potential is applied.

A great danger to this insulation is due to its gradual destruction by brush discharge from a secondary winding which has slipped. Eventually an actual spark may pass between adjacent inner secondary winding turns, which results in charring and eventual breakdown of the overheated portion of the primary tube.

## THE CONDENSER AND ITS ACTION

The condenser, shunted across the primary circuit contacts, is really a separate component of the induction coil high-tension generator, and is actually so, in the normal X-ray installation, with a separate interruptor. In the smaller coils, with a hammer or similar break, it is conveniently mounted within the wooden stand supporting the coil (Fig. 192B), to which short leads can be directly taken to the break.

For economy of space, the induction coil condenser is usually a plate condenser of tin, or other foil, with a dielectric of paraffined wax paper, or better, mica. It offers no special features over the usual flat type condenser, the only point in its design is that, as it is subjected to the retroactive voltage from the secondary during discharge, it must have a sufficiently stout dielectric to deal with this higher voltage and not merely that of the primary voltage.

For details of condenser manufacture Codd's book on induction coil design should be consulted.

The more reliable Leyden jar type of condenser would be preferable on this score, but unfortunately this requires too great a space.

In order to prevent high-frequency surges it should be as close to the

actual break as possible. It is therefore, in the larger coils, where the break may be at some distance from the actual coil, mounted near the break rather than near the coil.

The capacity is usually between one to two microfarads for the normal type of X-ray coil, but as this capacity shows one or more optimum values for best results, the actual capacity should be determined for the actual conditions of operation, by use of a suitable variable condenser. A fixed condenser of this value is then constructed, or obtained. Whilst never done in practice, it would be preferable to have actually two condensers, one a fixed condenser of the approximate value and an adjustable condenser of suitable proportions, to allow accurate adjustment when the actual running conditions are altered.

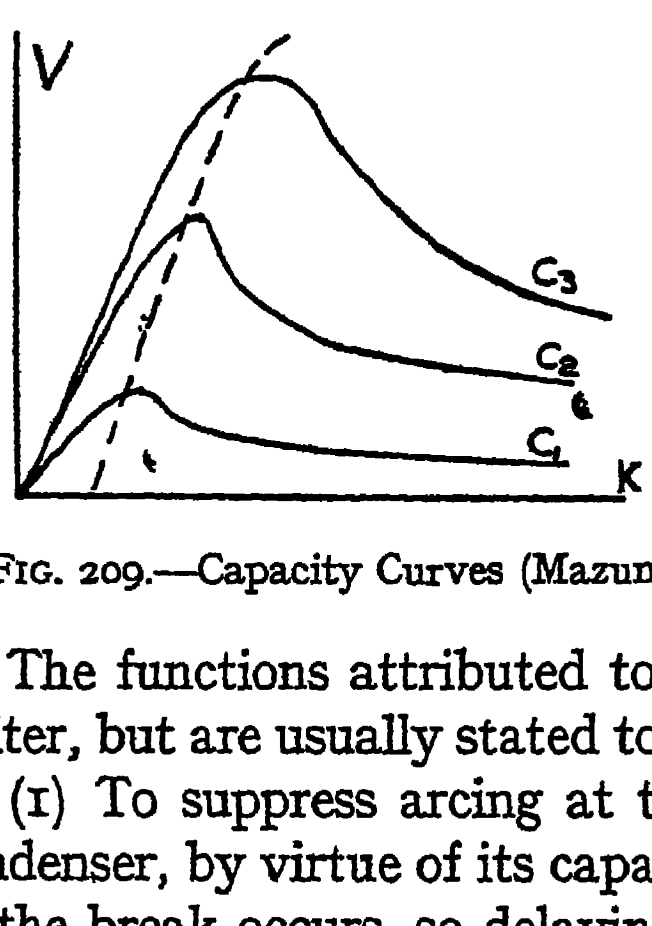



FIG. 209.—Capacity Curves (Mazuno).

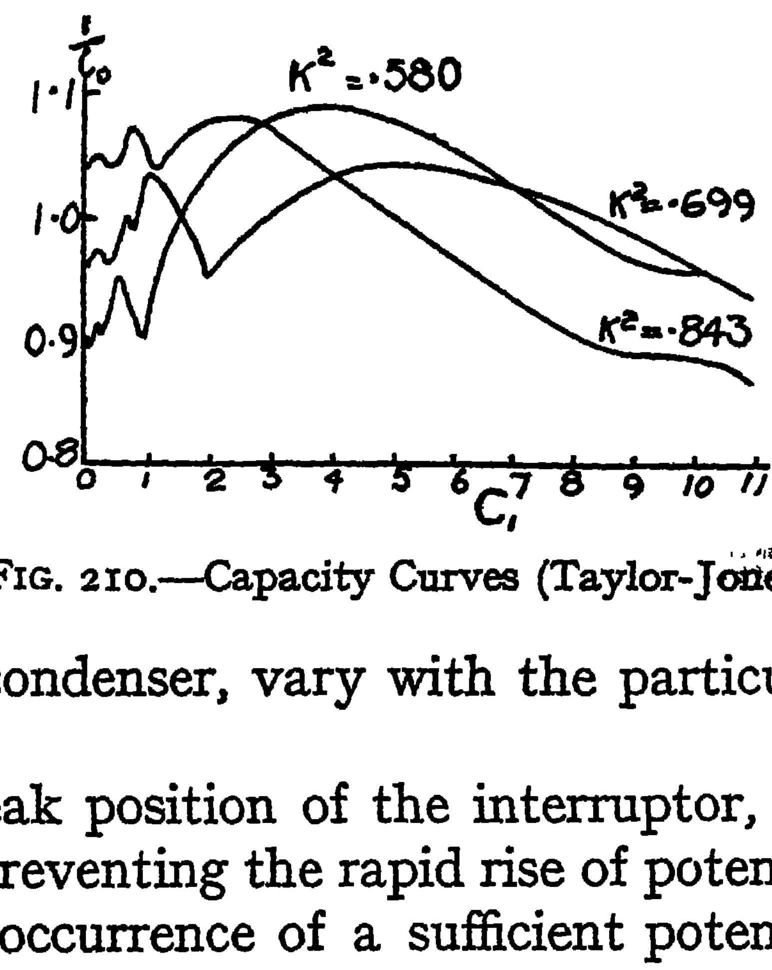



FIG. 210.—Capacity Curves (Taylor-Jones).

The functions attributed to this condenser, vary with the particular writer, but are usually stated to be ;

(1) To suppress arcing at the break position of the interruptor, the condenser, by virtue of its capacity, preventing the rapid rise of potential as the break occurs, so delaying the occurrence of a sufficient potential until the break contacts are well separated.

(2) Prevention of this conductive arc increases, as desired, the suddenness of the break. The reverse process occurs at the primary make, the condenser only allowing the slow growth of voltage, so that arcing does not occur before the primary circuit contact is well made.

(3) To retard the formation of induced currents in the primary, due to retroaction of the secondary circuit, the condenser acting as a reservoir against rapid rise of potential. Against this view however must be set the fact that it must aid the formation of oscillatory currents or surges, the inclusion of such a relatively large capacity in the inductive primary circuit, constituting an oscillatory type of circuit.

As regards the necessity of the break condenser we have contradictory views.

Mazuno * showed, in 1898, that the sparking distance, represented by V of Fig. 209, was dependent upon the primary capacity K. As the

* *Phil. Mag.*, 45, p. 447, 1898.

capacity was increased so the value of V increased to an optimum value, after which further increase of K caused decrease of V. The relative values of K and V were however dependent upon the actual primary current, as shown by the curves $C_1$, $C_2$ and $C_3$, which represent various values of current.

Lord Rayleigh,* in 1901 showed, in his mathematical theory of the induction coil that, with a sufficiently rapid rate of break, a condenser would be unnecessary, as is the case with the very rapid electrolytic break. Rayleigh put his theory to the test by interrupting the primary circuit by means of a rifle bullet and found no variation of spark length when the primary capacity was present or was absent.

More recently Taylor-Jones, to whom we owe the most complete analytical treatment of the induction coil from the mathematical aspect, has shown that, not only should there be an optimum value of capacity, even at such a rapid value of break, but there may be several optimum values as indicated by Fig. 210. Moreover, the value of this capacity will vary with the degree of coupling K (*q.v.*, Vol. I.) between primary and secondary circuit. Taylor-Jones equally put the Rayleigh theory to test, by interrupting the primary circuit by means of a bullet and obtained results, proving his theory that the primary condenser is of importance even at high rates of interruption.

The difference in these contradictory views is undoubtedly due to the method of analysis and the type of coil used for each experiment.

Rayleigh used for his theoretical treatment equations in which the primary and secondary circuit were tightly coupled so that the coefficient of coupling tended to unity. In such a tightly coupled coil the oscillation of current in the secondary circuit is a forced oscillation, independent of the natural frequency of oscillation of the circuit and, with these approximate equations the capacity can be shown to be zero for maximum secondary current. By a chance the particular coil used by Rayleigh in his experiments was of this tightly coupled type and the results therefore agreed.

Taylor-Jones in his theory of the coil used the more exact treatment, due to Overbeck, during the last decade of the last century, in which the two circuits are considered in relation to their coupling. This may vary from the forced oscillation when K = 100, to the case of the oscillation transformer when $k$ is tending to O, and the secondary circuit is no longer "forced," but selects the particular component of the total energy, which resonates with its own free period of oscillation. Equally by chance, Taylor-Jones used a loosely coupled type of induction coil and found his results agreed with this more extended treatment.

During the interval between the work of Rayleigh and Taylor-Jones every writer has stated that the capacity is of no importance at rapid rates of break, showing the incorrectness of generalising, without question, results obtained by even such a high authority as Rayleigh.

* *Phil. Mag.*, 2, p. 581, 1901.

It is unnecessary to enter into the mathematical treatment of these two views and, it is questionable, whether, owing to the impossibility of ascertaining exactly the relative magnetic fields of the primary and secondary circuit, that a complete mathematical theory and therefore a complete design theory can ever be obtained.

To the practical radiologist owing to the gradual decline of the use of the induction coil such a theory, if obtainable, is of purely academic interest, particularly as, for its appreciation some degree of higher mathematical reasoning is necessary.

Similarly, from the aspects of practical experience we have R. S. Wright,* an experienced manufacturer, stating that the more rapid the rate of interruption the less the need of a condenser, which is entirely absent with the electrolytic break. Equally Codd states the converse from practical experience.

W. H. Wilson † found that with a coil with a condenser and having a magnetic energy just insufficient to cause sparking, a spark could be obtained without a condenser, a result which may be held to confirm Rayleigh's theory or, since the primary circuit must have some inherent capacity which alone may tend to the optimum value, may equally be held to support the Taylor-Jones theory.

The only useful practical result is that the optimum capacity should be determined by trial for each particular coil and, this capacity must vary with its rate of interruption, *i.e.*, be of a certain value for slow rates of interruption and perhaps absent for rapid rates of interruption.

Moreover the more precise measurements of Taylor-Jones at low rates of interruption, show that no useful and more probably a harmful effect is produced by too large a value of primary capacity.

## THE SYMMETRICAL OR DUPLEX COIL

The symmetrical or duplex type of coil has been very much used in therapy radiology of recent years following the deep therapy boom. As this was one of the types of apparatus manufactured by Reiniger, Gebbert and Schall, of Erlangen, it has been very largely copied in England. Actually it is only a modified revival of one of the types of coil used many years ago by Klinglefuss.

The original " symmetrical " apparatus is shown in Fig. 211, which illustrates how the windings are divided into two equal or symmetrical sections, each with its own core.

The advantages which result, when it is desired to generate very high voltages for therapy purposes are chiefly as follows ;—

(1) The winding being split into two approximately equal portions,

* R. S. Wright, *Jour. of Rönt. Soc.*, Vol. 17, p. 76, 1921.
† W. H. Wilson, *Proc. Roy. Soc.*, Vol. 87 (1912), p. 76.

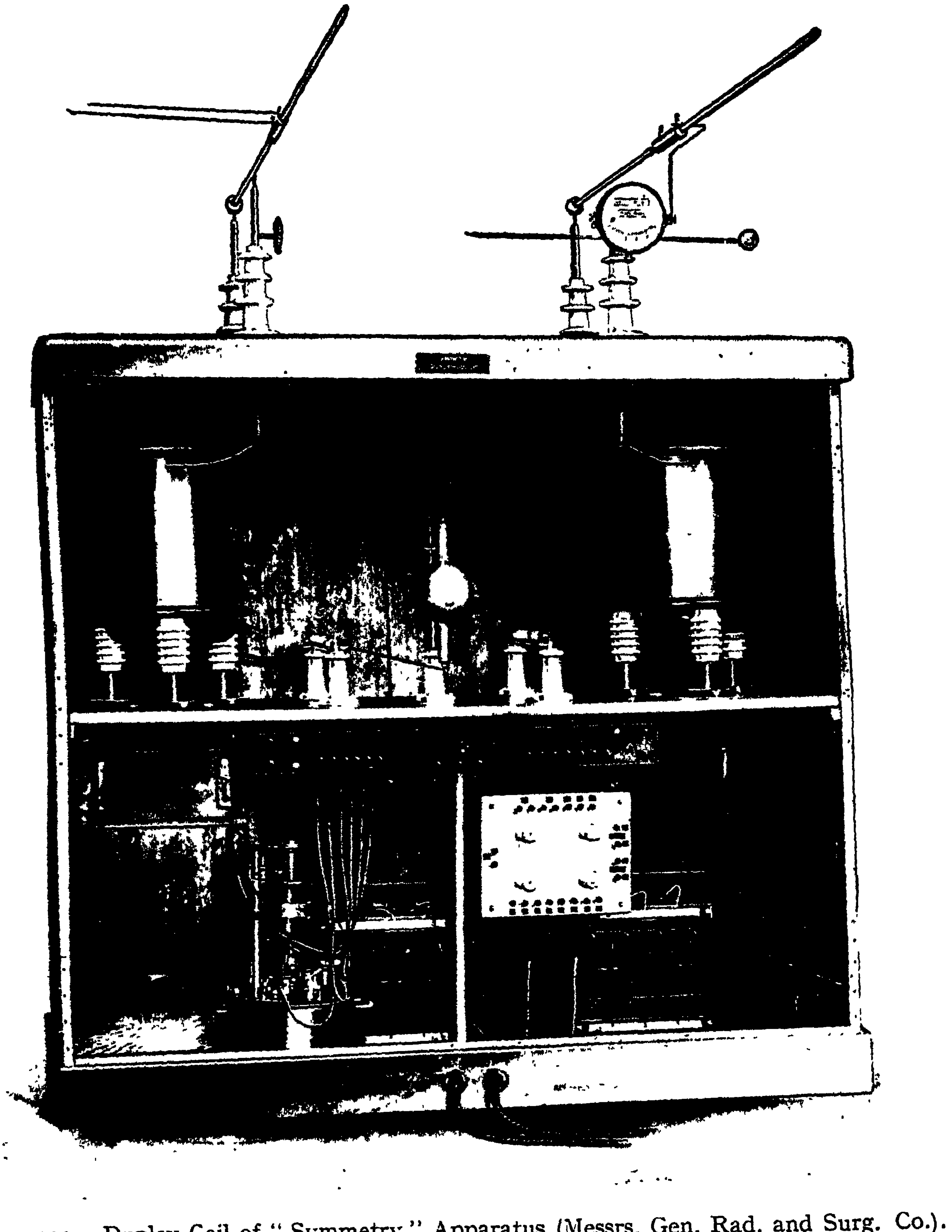


FIG. 211.—Duplex Coil of "Symmetry" Apparatus (Messrs. Gen. Rad. and Surg. Co.).

[*To face Fig*. 212, *between pp*. 276 *and* 277.

current is halved the self induction becomes equal to its previous value, but the magnetic field is also now only equal to its series value and no useful effect results, whilst meantime the parallel primary winding can no longer be earthed.

Codd's argument that, by this means, the self induction is halved and the make and break can occur more quickly does not hold on closer inspection. Were it true, trouble would be experienced in the secondary circuit, due to the lower self induction allowing a much more rapid and high voltage rise of inverse voltage at the moment of make.

Whilst this duplex method has undoubted advantages, we must note that as the core's length is decreased the demagnetising effect will be greater and so the efficiency will be lowered, this demagnetising effect now being exerted at four coil ends instead of two. On the other hand this has the advantage that, during the break period, the primary demagnetises more rapidly and the rate of interruption may if desired be increased. This increased output due to the latter effect may necessitate an increase in the core areas to avoid larger hysteresis losses at this increased frequency of working.

The inverse current obtained with this form of apparatus, probably due to the rapid demagnetisation by four open poles, necessitates the provision of one or more valve tubes and, to deal with the increased rate of interruption, a particularly heavy form of interruptor with a large capacity across the break is used.

The duplex coil has been rendered still more like the old Klinglefuss coils, by immersing the coils in oil so, as in the case of the oil-immersed transformer, reducing the effect of brush discharge and reducing insulation distances. One example utilises porcelain containers.

It is generally stated that enclosing the coil in a metallic chamber has a harmful effect. Crowther* however states, from the results of experiments, that no variation resulted in the operation of such a metal-cased coil, when the container was removed. The type of coil Crowther used was however of a highly damped forced aperiodic type and variations may possibly occur, when an oscillatory transformer type of coil is used, owing to the high-frequency oscillations setting up eddy currents in the container.†

For economy of space and oil it is a further step to include both coils in a single container, and we arrive at the old Tesla oscillation transformer ‡ used prior to the discovery of X-rays, which can be used either with interrupted direct current or alternating current.

Similar coils have been constructed by Rochefort and Wydt who, in addition to oil-immersion, impregnated the windings with a paraffin wax mixture.

* J. A. Crowther, *Brit. Jour. Rad.*, 21, p. 66, 1925.

† R. S. Wright in a personal communication to the Author states that a metal container makes the coil discharge far more oscillatory.

‡ N. Tesla, *Journ. Inst. Elect. Eng.*, 21, p. 62, 1892.

iron, for which the hysteresis and skin effect would be large and cause heavy damping and rapid cessation of oscillatory discharge.

Another method of rapid interruption used was, following Rayleigh, by means of revolver bullets, various apparatuses having been evolved, none of which have ever come within the range of practical medical radiology.

During the " single flash " period many monster coils were produced, most of which were based upon entirely erroneous conceptions.

All these coils aimed at inducing a very high secondary voltage of 25 in. and above corresponding to peak voltages of over 300 kv. When it is remembered that the most effective photographic result in the normal silver bromide plate, is produced by a radiation emitted by only a few tens of kilovolts, the general result of these highly penetrating radiations, which passed through the tissue and photographic emulsion without great effect, was only to render definition bad, by increasing the scattered radiation.

To suppress the large inverse current valve tubes were utilised. At the time of writing there is, in one of the larger London hospitals, such a mammoth coil which employs a battery of at least ten to twenty valve tubes. This hospital must take 50 per cent. of the English manufactured valve tubes and provide a lucrative source of revenue for the tube manufacturer. It has apparently never yet been discovered that, with the particular arrangement used, a voltage of over 300 kv. is commenced with from the secondary coil terminals, and the insertion of this large number of valve tubes must reduce this voltage to a fractional kilovoltage. The only result of this highly expensive coil is to so waste energy and destroy expensive valve tubes. A much better result would be obtained with a small and cheap heavy secondary current coil.

When we come to examine the requirements of the so-called single flash coil the requirements are seen to be ;—

(1) A core of very large area, so that the secondary coil encloses a very large number of lines of magnetic flux.

(2) The core should be short so that the demagnetising effect at break is large.

(3) The primary windings should be of very heavy gauge wire to carry a very large magnetising current, so increasing the core flux.

(4) The number of primary turns should be relatively small, to lower the self inductance of the primary and to allow rapid discharge of flux at break.

(5) The primary tube must be increased in thickness to avoid breakdown, by the sudden rise of potential.

(6) The secondary voltage must not be too high, but the current-carrying capacity considerable. As regards the latter, the above suggested use of high-resistance iron wire would oppose this, but it would be a matter

adopted a much more practicable method * in which the primary circuit is equally divided and the coil interruptor is coupled to a high-tension rectifying disc. The primary current is, by the interruptor, periodically reversed in direction and alternatively supplies each half of the split primary, the direction of the resulting secondary current being commuted by the high-tension rectifier.

The practical result is that the periodical reversal of the primary current causes the growth of magnetic flux in the core to be assisted by the inverse current due to the magnetism of the other winding which has previously caused magnetisation and, at the same time, the high-tension rectifier prevents the flow of inverse secondary current *viâ* the X-ray tube. The net result is essentially to increase the frequency of interruption possible and so to give an increased output in unit time.

An analogous method is shown in the " Rectipulse " coil of Fig. 217.

## THE WILSON COIL

This is a novel form of coil which has been used in the smaller wireless transmitters of the portable type and is stated to be suitable for X-ray purposes.†

It does not however appear to have come into any extended use for X-ray purposes and, probably at the higher voltages needed for this purpose, the commutating arrangements would be rendered difficult owing to arcing.

The connections are as Fig. 218. A direct current source 3 supplies an oscillatory circuit comprising an inductance 2 and capacity 7, the resistance of the circuit being kept low, to give the conditions for oscillatory discharge (see Chapter V., Vol. I.).

It can be shown mathematically ‡ that, at the end of the first half-wave of oscillation, if the resistance is negligible, the condenser 7 will be charged to 2V, if V is the voltage of the battery 3. At this instant the energy stored by the inductance 2 is zero and the interruptor 4 can break the circuit at a moderately low voltage without sparking and with no retroaction from the secondary circuit.

The charge upon the condenser 7 is now free to oscillate in the circuit 7 and 8 at the natural frequency of this circuit. At the end of the first half-wave of this free oscillation, neglecting losses, the condenser is reversely charged to + 2V and, if it is arranged for the commutator to again close the circuit 2 and 3, at this moment the voltage 2V of the condenser is added to that of the supply, giving a total voltage 3V across the inductance 2. Hence an increased amplitude of oscillation occurs and

* Brit. Patents 7,311/1915 and 175,460/1920.
† W. H. Wilson, *Jour. Rönt. Soc.*, 18, p. 143, 1922.
‡ H. Starke, *Zeits. f. Tech. Phys.*, 3, p. 214, 1922.

Essentially this commutated condenser method gives a four-fold stepping-up of the primary voltage, a result which is equally obtainable by the use of a larger transformation ratio either in the secondary itself, or by transforming the interrupted direct current in a small intermediate transformer of a ratio of 4. Such a method allows the high-speed interruptor and its mechanical complications to be dispensed with. Whilst the efficiency is not stated and may be higher than the normal coil, this is unlikely to be very much greater, owing to the use of an open core, since the output is dependent upon the input, *i.e.*, upon the size and capacity of the accumulators. Hence no great advantage for the more intricate operation appears to result. A still greater efficiency would result by the use of a small oil-immersed transformer pure and simple, with a small rotary converter (easily portable) working off the same accumulator battery as in the modern Coolidge portable X-ray apparatus, where, owing to the rectifying action of the tube a rectifier is totally unnecessary with alternating current.

## EXERCISES ON CHAPTER V

*Questions 1 to 5 are based upon analogous questions set in the D.M.R.E. Examinations of Cambridge.*

(1) Describe how an induction coil is constructed. By means of a wave-form diagram show the effect of a condenser in parallel with the interruptor upon the secondary current.

(2) What is self-induction? What is the effect of induction when a circuit is made and broken and discuss the bearing upon the action of the induction coil?

(3) Define permeability, magnetic induction, intensity of magnetism. What do you understand by a "line of magnetic induction," and how do these lines pass in an excited core of (*a*) an induction coil core, (*b*) a transformer core?

(4) Give the principles underlying the action of an induction coil. How does the secondary voltage differ in coil and transformer and discuss their relative merits and demerits for X-ray tube excitation?

(5) Define (*a*) power, (*b*) energy of an electric circuit. An induction coil primary takes 16 amperes at 100 volts and the secondary gives 6 milliamperes at 80 kv. What is the approximate efficiency of this coil? Discuss why the method is approximate only.

(6) If the condenser belonging to a coil outfit broke down, what effect would it have upon the secondary circuit and how would you detect the fault? (Soc. of Rad. Exam., December, 1923.)

(7) Describe, with diagram, how a rectifier cuts out inverse current in the secondary circuit. (Soc. of Rad. Exam., June, 1925.)

(8) Describe the construction and mode of action of an induction coil. (Soc. of Rad. Exam., July, 1922.)

(9) Discuss the action of the break condenser of an induction coil.

(10) Describe and state the advantages of the Klinglefuss closed core induction coil. Why is the core not completely closed?

(11) What are the design requirements of the single flash induction coil?

(12) Describe the therapy duplex induction coil.

arise as in Fig. 220 (1) where the secondary voltage tends to fall at an exponential rate; Fig. 220 (2), where a considerable inverse voltage, due to primary current growth is shown; Fig. 220 (3), where the occurrence of voltage peaks is shown, the voltage falling and rising several times before final decay. In Fig. 220 (4) such peaks have developed into a series of separate partial discharges which are unidirectional, but may actually oscillate, as in Fig. 220 (5) and (6), if the circuit characteristics are favourable.

If the coil is loaded with a gas tube, an original high value of voltage is necessary for the breakdown of the tube's vacuum, but, once ionisation and decrease of resistance occurs, the secondary voltage falls to a lower value. In consequence of the removal of the available electrons the voltage may again rise to subsequently fall to the zero value as Fig. 220 (3).

As the voltage curve is indirectly a measure of the resulting X-ray quality and quantity it follows that, the more rapidly this cycle is completed, *i.e.*, the greater the frequency of interruption per unit time, the greater is the energy output of the coil. Similarly the more rapid the cycle of interruption, the more rapid is the flux change, and the greater the resultant secondary e.m.f. and the current *viâ* the X-ray tube.

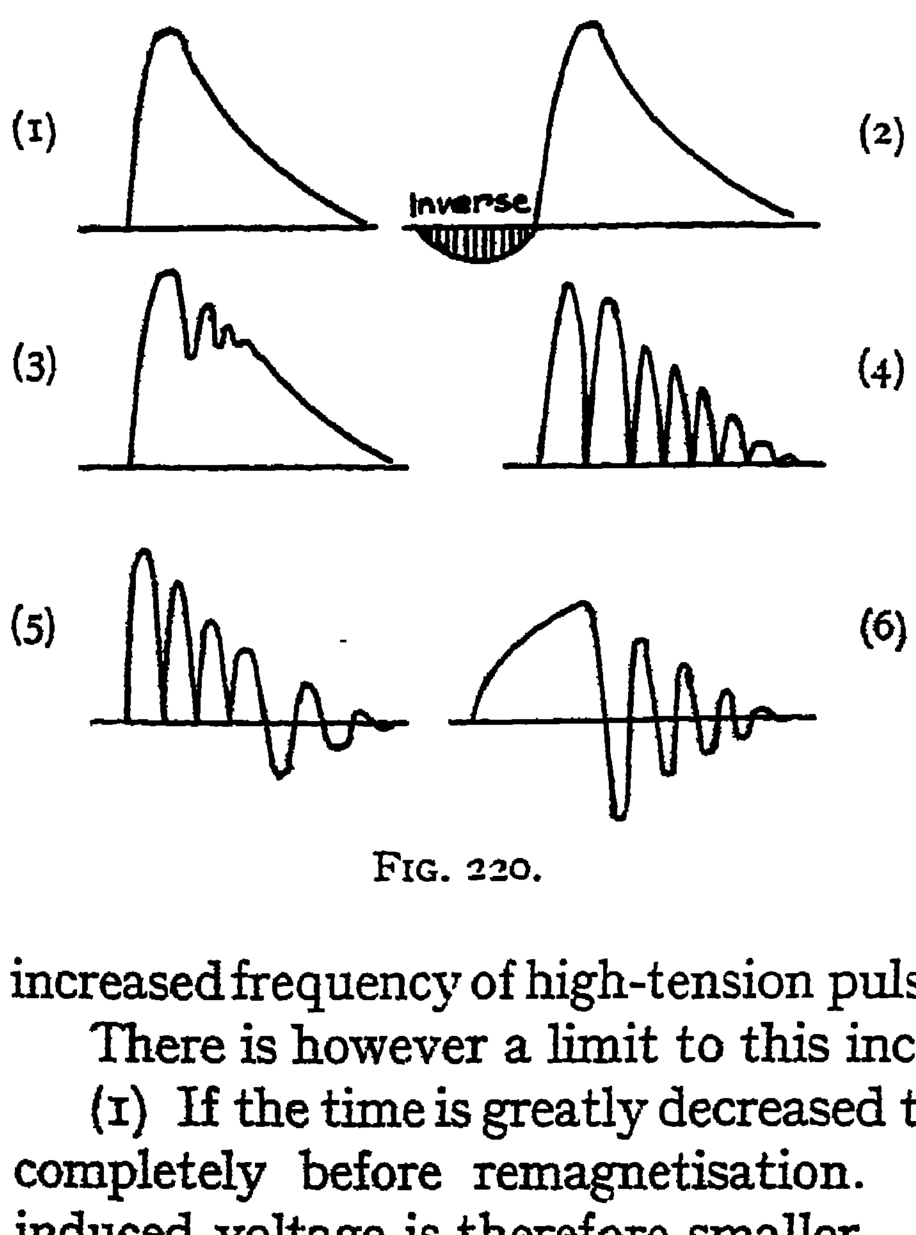


FIG. 220.

Increase of frequency of primary interruption therefore gives rise to increased secondary output, due to both the effect of increased frequency of high-tension pulses and increased value of each pulse.

There is however a limit to this increased output since ;—

(1) If the time is greatly decreased the core has not time to demagnetise completely before remagnetisation. The resulting flux variation and induced voltage is therefore smaller.

(2) Subject to (1) mechanical difficulties are experienced with more rapid rates of interruption, owing to arcing, etc.

Actual oscillographs will often show the presence of many irregularities in the voltage curve of the secondary due to actual oscillations occurring in the tube as in Fig. 220 (5), and it is common for the energy to surge to and fro between the secondary and primary circuit, a condition of affairs which is shown by the type of curve (Fig. 220 (6)), and which could be prevented by the use of some form of damping spark gap or better, although never used, a "quenched" type of gap (*q.v.*, Vol. I.).

To prevent inverse current passing *viâ* an X-ray tube we have various methods ;

(1) Insertion of the gas type of valve tube. This results in a great lowering of potential by virtue of its inherent resistance.

(2) Insertion of the electron type of valve tube which exerts a comparatively negligible resistance and completely prevents the inverse current, if the energy passing is not sufficient to cause heating and emission of electrons by the anode.

(3) Insertion of some form of spark gap. This (of the plate and point type) is rarely used owing to its objectionable noise. For this reason the rapidly quenching practically noiseless gap of Wien would be most advantageous, although this necessarily introduces resistance into the circuit.

(4) Usually convenient methods of mechanical rectification of inverse current, which are however inefficient.

(5) By far the best method is by correct coil design, so that inverse is reduced to a minimum, combined with a slow velocity of make and rapid break.

It cannot be too well borne in mind that the secondary energy of an induction coil is ;—

(1) Partly oscillatory.

(2) Partly aperiodic.

The relative energy partition between oscillatory and aperiodic discharge depends largely upon the electrical values of the secondary circuit capacity. The capacity between layers of coil windings increases the tendency to oscillatory discharge and resistance, as of a spark gap, decreases the growth of oscillatory energy, undesired in X-ray work.

When such oscillations are present, as the alternative spark gap is more easily broken down, owing to the decrease in dielectric value of the air between the electrodes, the spark gap must be opened to prevent discharge. A higher apparent voltage is so obtained but this is not a real increase. Similarly, as the current reading, with an electromagnetic instrument, is the difference of the current flow in reverse directions, this reading will be lower than the actual total current and useful current.

A hot wire instrument, being dependent upon both components will conversely read too high.

The difficulties of apportioning the useful component to the total component renders all induction coil current readings, like voltage readings, open to much question. For example a low induction coil reading may compare very favourably to a higher transformer reading in therapeutic effects, but actually the current may be greater than that of the transformer current.

Conversely the higher voltage shown in the induction coil may be

As already dealt with in the last chapter, a condenser is shunted across the break in order to absorb energy and prevent arcing.

The rate of vibration is dependent upon the mechanical elasticity of the spring carrying the hammer, and the length of path between the fixed contact and core, between which the hammer moves.

Such a break will work satisfactorily at comparatively low values of retroactive primary voltage, which in turn depends upon the actual secondary voltage and for low rates of interruption. It therefore finds application in coil wireless transmitters where these conditions are fulfilled but is of little or no use for X-ray purposes.

The break shown in Fig. 222 has a spring *c* the natural frequency of which coincides approximately with the desired number of interruptions. Such breaks, known as *syntonic* breaks, operate to give the coil discharge the frequency of their own period of oscillation in contradiction to *atonic* breaks, where the hammer spring is heavily damped and the period of vibration is imposed upon the break by the coil itself and not *vice versâ*.

With improvements in radiological technique and apparatus, the irregularity of breaks of the Apps type, soon caused the limits of their usefulness to be reached, and their replacement by one or other forms of mercury break, which at the present day, is the most widely used type.

## MERCURY BREAKS

*The Dipper Break.*—This is really a development of the Apps break and the early forms took the type of Fig. 223. The current in the primary circuit is passed *viâ* a solenoid S entirely separated from the coil itself. This solenoid, when the current is made, attracts an armature A connected with a lever AB, pivoted at P, *viâ* which the primary circuit is completed through a container of mercury by a contact D.

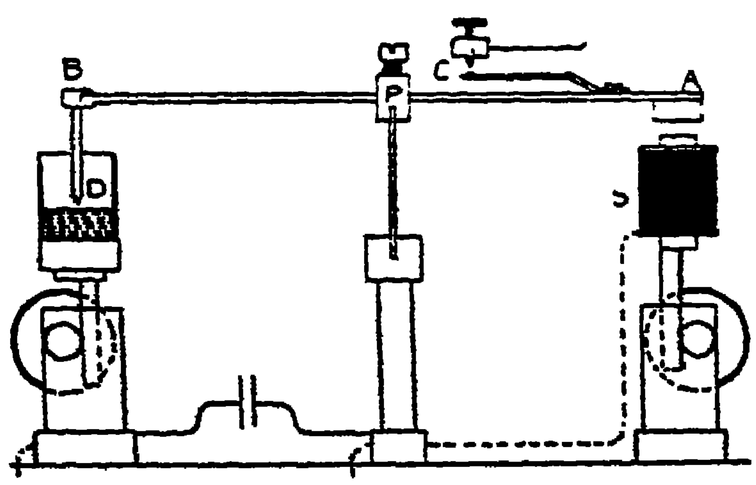



FIG. 223.—Dipper Break.

When the attraction of the solenoid occurs the lever moves and draws a contact D out of the mercury. This breaks the primary circuit until, the solenoid attraction having so ceased, the lever contact again falls into the mercury and recompletes the primary circuit.

The objection to this primitive mercury break is its irregularity since any change of primary current is reflected in the solenoidal attraction. The frequency of break so varies with the input energy. Also, owing to splashing of the mercury and its being set into violent movement, irregularities again occur and the frequency of interruption possible is limited.

leaves the mercury pool so the primary circuit is made or broken. The wheel is motor driven and is, for its operation, entirely independent of the induction coil. The speed of interruption can be widely varied, independently of the coil, by regulating the motor speed.

The ratio of make and break periods varies with the proportional sectorial areas of the rotating contact to the total area of the wheel and, to a less extent, upon the depth of mercury. This ratio was capable of determination both during construction or by regulation of the mercury level when in use.

A modern form of dipper break is shown in Fig. 224B. A similar type of dipper break is shown in Fig. 225, the principle of which is essentially the same, three vanes making simultaneous entry into the pool of mercury within H. These parallel contacts allow the passage of a larger primary current. By spacing these vanes symmetrically around the shaft, a much greater frequency, controllable by the motor speed, may be obtained.

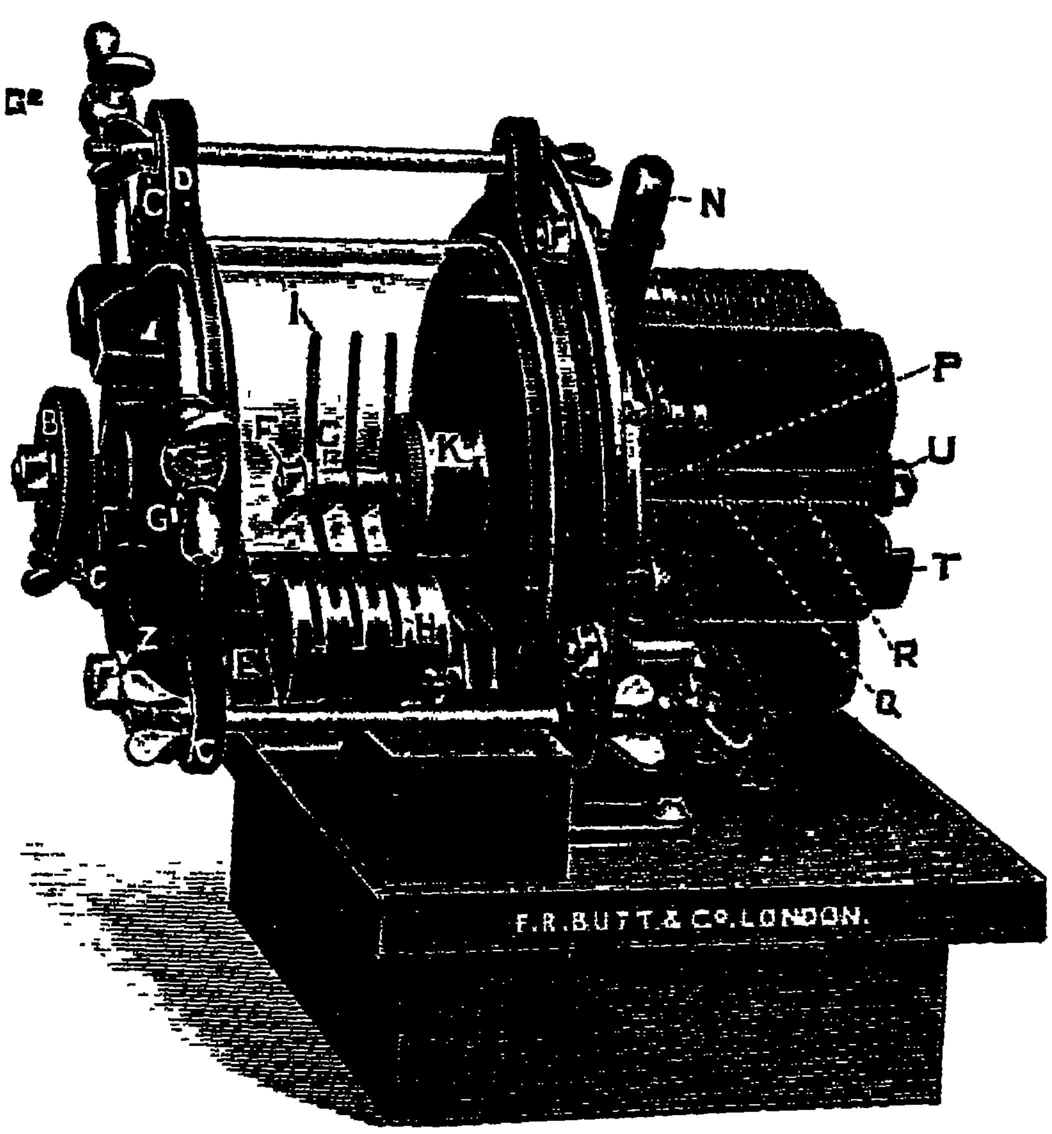


FIG. 225.—Magnetic Driven Dipper Break.

Where the arrangements permit it is usual to float a metal washer upon the mercury to damp out the splashing. The mercury is usually covered with alcohol D (Fig. 224A) to aid the damping of the spark.

*The Centrifugal Break.*—This is not greatly used in practice, the jet or turbine break being more commonly preferred.

Essentially it consists of a steel bowl A (Fig. 226A) mounted vertically above, and rotated by, a motor beneath, the whole being suspended by spring hooks. The bowl contains about 10 oz. of mercury covered with paraffin oil, to prevent and to quench sparking. As the bowl rotates the mercury, by centrifugal action, ascends the sides to lie in a channel so that a ring of mercury is formed.

Into this ring of mercury protrudes an eccentric fibre wheel B mounted upon ball bearings with a metallic segment C as in the Mackenzie-Davidson break and fixed upon a central shaft.

The oldest type is that of Levy in which a fixed jet sprays mercury upon a number of rotating triangular segment contacts (Fig. 227),

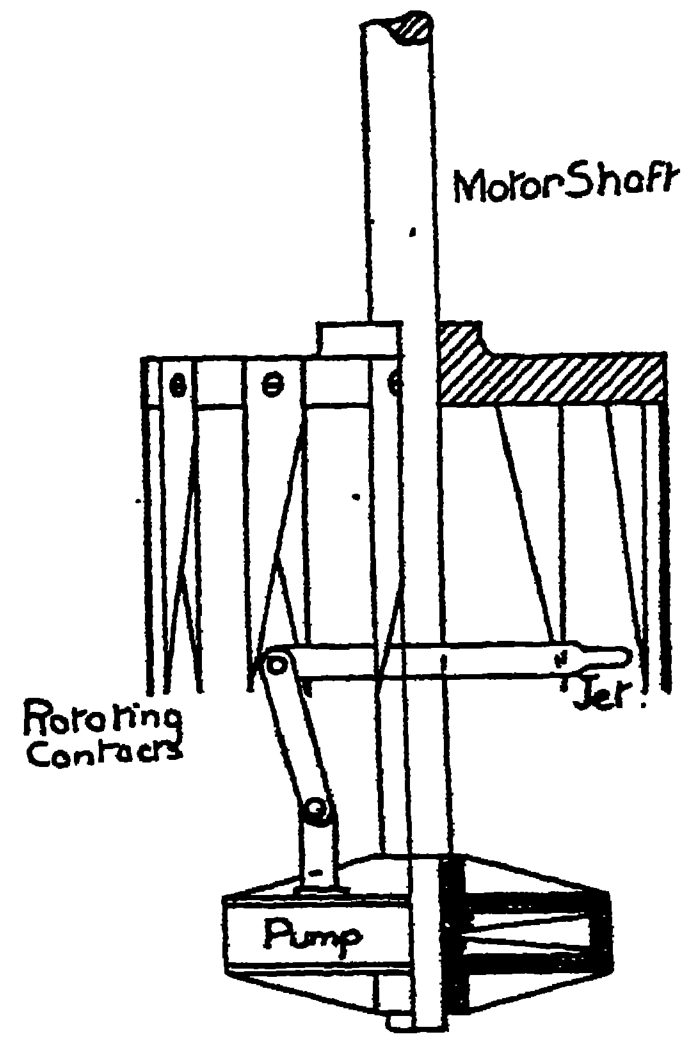



FIG. 227.—Levy Jet Break.

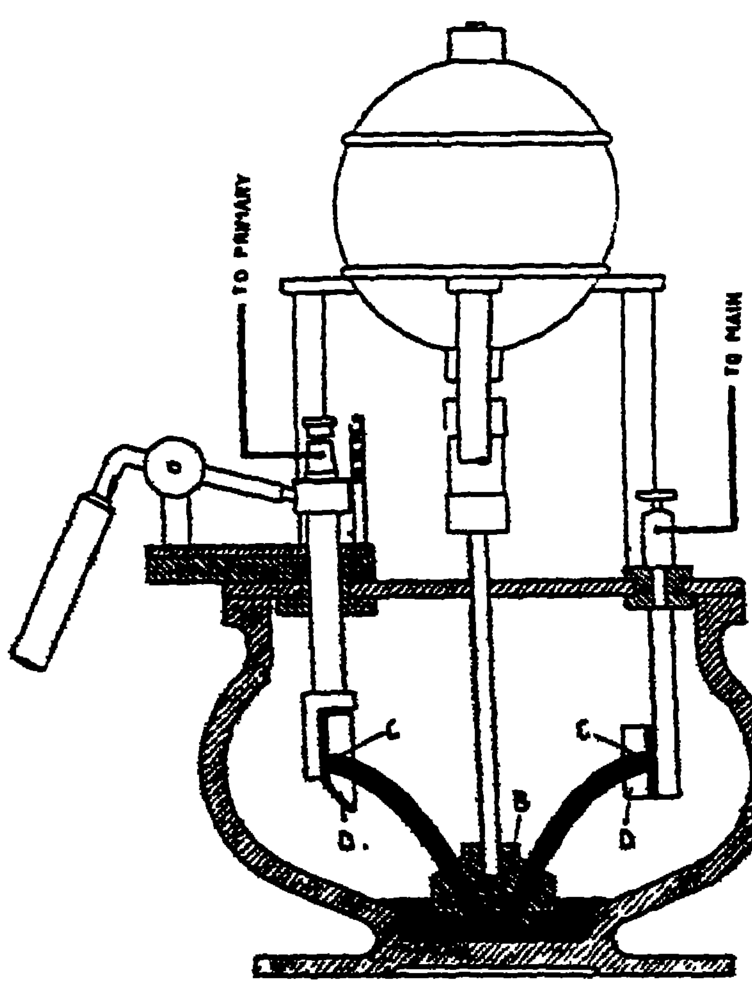



FIG. 228A.—Turbine Break (Messrs. Schall).

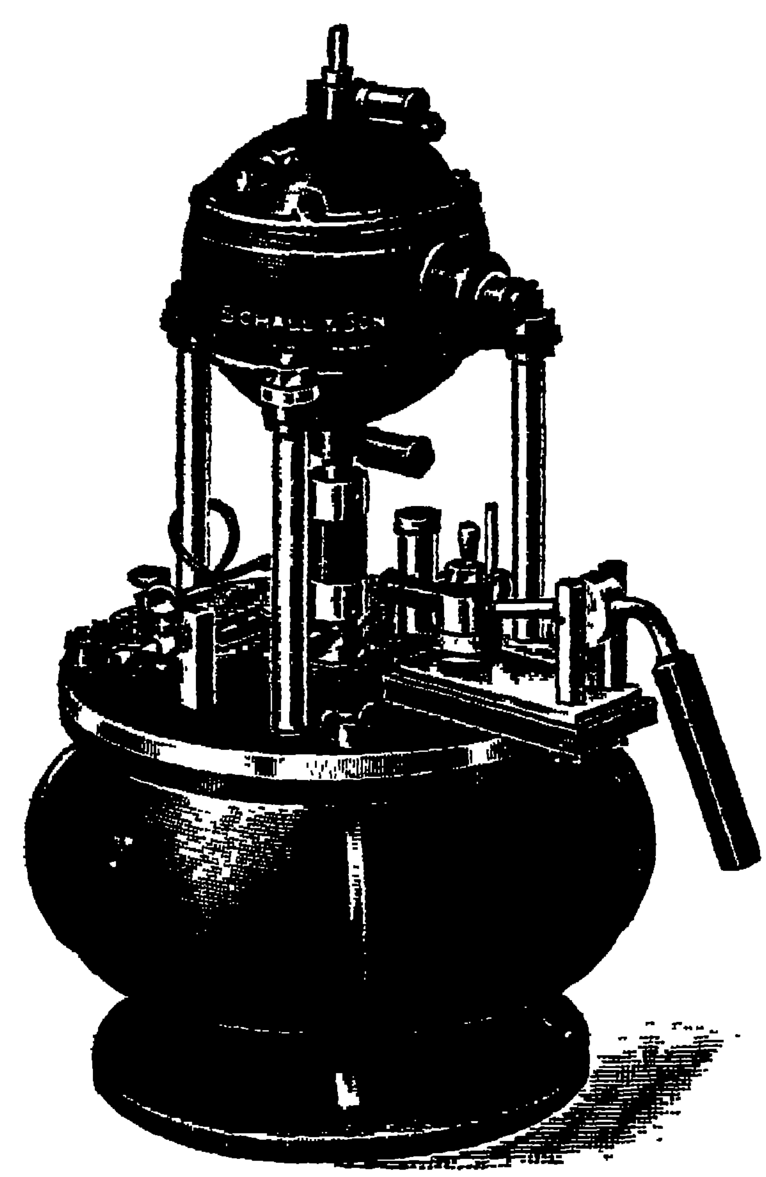


FIG. 228B.—Turbine Break (Messrs. Schall).

the circuit being completed *viâ* jet, mercury and segment opposite the jet.

form and the time of make is varied by their being raised or lowered by the insulated handle shown with a lock.

This movement is obtained by means of a piston operated by the insulated handle to permit of the electrodes being lifted completely out of the mercury and so to interrupt entirely the action of the coil, if this is desired.

An essential feature is the covering of the lower jet orifices by means of strainers, to prevent the sludge and oxide, that forms upon the mercury, from blocking the jets, a trouble to which all jet interruptors are liable.

A resistance in the motor field controls the speed of the motor usually between 1,000 and 1,500 r.p.m. The frequency of interruption may be so varied between 2,000–3,000 per minute, *i.e.*, up to 50 per second.

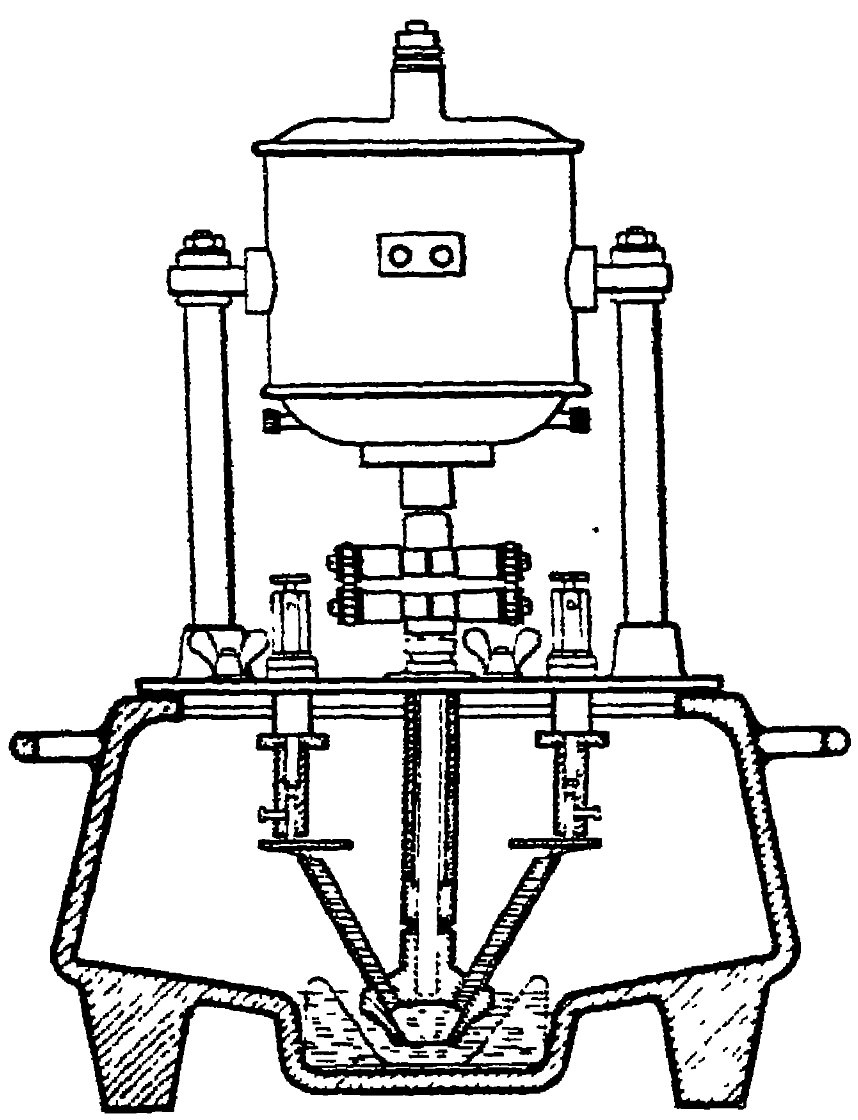


Fig. 230.—Constant Interruptor (Reiniger, Gebbert and Schall).

Codd after a suggestion of Philips has evolved a jet interruptor (Fig. 229) in which the motor is below instead of, as usual, above the interruptor. This permits more easy access to the interruptor proper for cleaning, adjustment, etc.

It is claimed as a further advantage that the chamber top may be of specially strong glass to allow inspection during running, but this, even with Triplex glass, increases the risk if explosion occurs, when, as usual, a gas dielectric is used.

With all jet interruptors the great drawback is the tendency to clog, and Reiniger, Gebbert and Schall in their "constant interruptor," for use with their deep therapy "symmetry" apparatus, use a U-shaped jet (Fig. 230). This is of relatively large diameter (8 mm. as against a usual diameter of about 1·5 mm.). The circuit is completed *viâ* an electrode above the jet, by the overflow of the mercury after its ascent of the U-shaped incline.

Codd* has described a rapid interruptor in which the jets are rapidly rotated with respect to the copper segments, rotated in the reverse direction. Whilst this increases the speed of interruption, the same effect could be obtained with less mechanical complication by increasing the motor speed twofold.

* Codd, *Rönt. Soc. J.*, 17, pp. 76, 1921.

This relation to a motor is more evident from a larger type of break on the same fundamental principle (Fig. 232) having a number of solenoids, essentially similar to the field coils of a motor, and a four-pronged armature. The *modus operandi* is the same.

This increase in number of the solenoids, fed by the coil direct-current circuit ensures a more regular rotation of the armature.

Whilst such automagnetic interruptors economise both weight and space as compared to the heavy motor-driven breaks, they are so erratic in action that they have not come into extended use, it being more certain and convenient in portable installations, to have a motor-driven interruptor and by means of series and parallel working, or resistances, to arrange for this to work off the more common voltages.

*The Quenching of Interruptor Sparking.*—A short summary of the conditions which affect the formation of a spark or a continuous spark known as an arc has already been given in Chapter VI., Vol. I.

The phenomenon is actually a very intricate one.

When the primary circuit of an induction coil is rapidly made or broken there is, owing to the rapid induction effect not only the production of a spark but also the liability to a permanent arc. Since this arc is highly conductive, the rapid interruption of the primary circuit is prevented and the resultant induced secondary e.m.f. is smaller, the effect being more pronounced if retroactive surges of high voltage occur in the primary circuit by virtue of the secondary mutual induction.

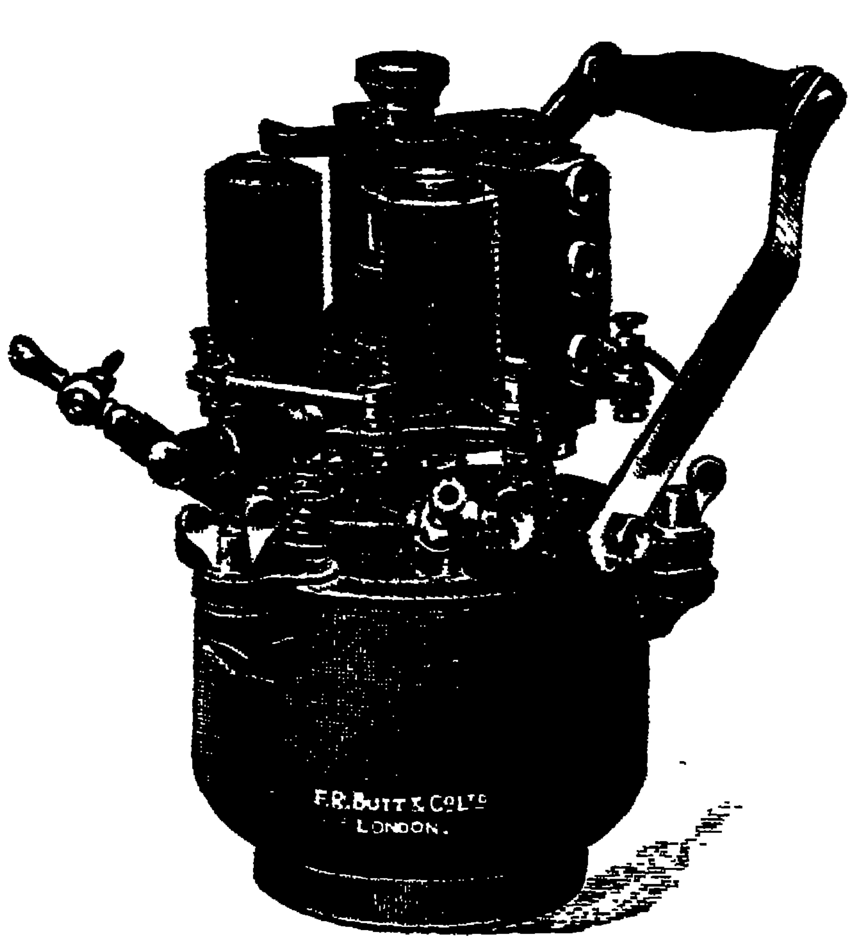


FIG. 232.—Auto-Magnetic Break.

Such arcing in an interruptor has the following disadvantages ;—

(1) It delays the sudden interruption of the magnetising current and so reduces the secondary voltage induced.

(2) It causes disintegration of the contacts and gradual alteration of the sparking distances with consequent irregularity.

(3) It causes oxidation of the mercury. The slag-like oxide formed is a bad conductor and at the same time is very liable to choke the jets. This is a further source of irregularity.

The subject of arc and spark establishment and maintenance has been much studied in wireless technology. It has been found that by causing the spark to occur in certain gases, and particularly in hydrocarbons, obtained from the decomposition of alcohol and other hydro-

is removed and straining *viâ* linen to be the best, this being the common method in physical laboratories. Failing nitric acid, strong caustic soda solution may be used.

To prevent further arcing it is necessary to shunt the actual spark gap by a condenser of suitable capacity as in the hammer break.

The automatic insertion of resistance in the primary circuit, necessary with very rapid "single flash" breaks, has already been described together with the special needs and features of "single flash" breaks, which usually employ an oil dielectric.

*Adaption of the Induction Coil to an Alternating Current Supply and Suppression of Inverse Current.*—The more economical generation of alternating current at high potentials and its subsequent transformation, tends to displace the older direct-current system of electrical supply.

Direct current may not therefore be available, and it is often necessary to run an induction coil apparatus with an alternating current supply. This is directly impossible since the coil then acts as an ordinary transformer, and the "inverse" current *viâ* the tube equals the correctly directioned current of the half cycle flowing from anode to cathode of the X-ray tube.

There are various methods of utilising alternating current for induction coils which are ;—

(1) Use of some converting machine as a rotary convertor or motor generator. This is expensive and renders the apparatus more complicated in operation, but is the most satisfactory.

(2) Provision of a rectifying apparatus in the low tension-circuit.

(3) Provision of a rectifying apparatus in the high tension-circuit.

Dealing with method (2), for this purpose a synchronous alternating-current motor is used.

We have seen (Chapter V., Vol. I.), that such a motor receives its name, since its rotation is synchronous with the varying of alternating voltage and current.

At any point in its armature's revolution, when it has obtained synchronous speed, there is a certain constant direction in which the current will then be passing. If we mount the rotating contacts of the mercury interruptor upon the rotor shafts of such a motor, it is easy to select, either by theoretical or practical means (see the transformer rectifying disc), appropriate positions such that, when the contacts in the coil primary are made, the current is flowing in a certain direction. Further rotation of the rotating contacts can then be caused to break or reverse the circuit, for a sufficient period, during which the reverse half cycle of alternating current is made, after which, the contacts are again made during the period of the correctly directioned half cycle.

Whilst it would be possible to utilise the other half cycle, such a utilisation may have no useful effect as the too rapid sequence of recti-

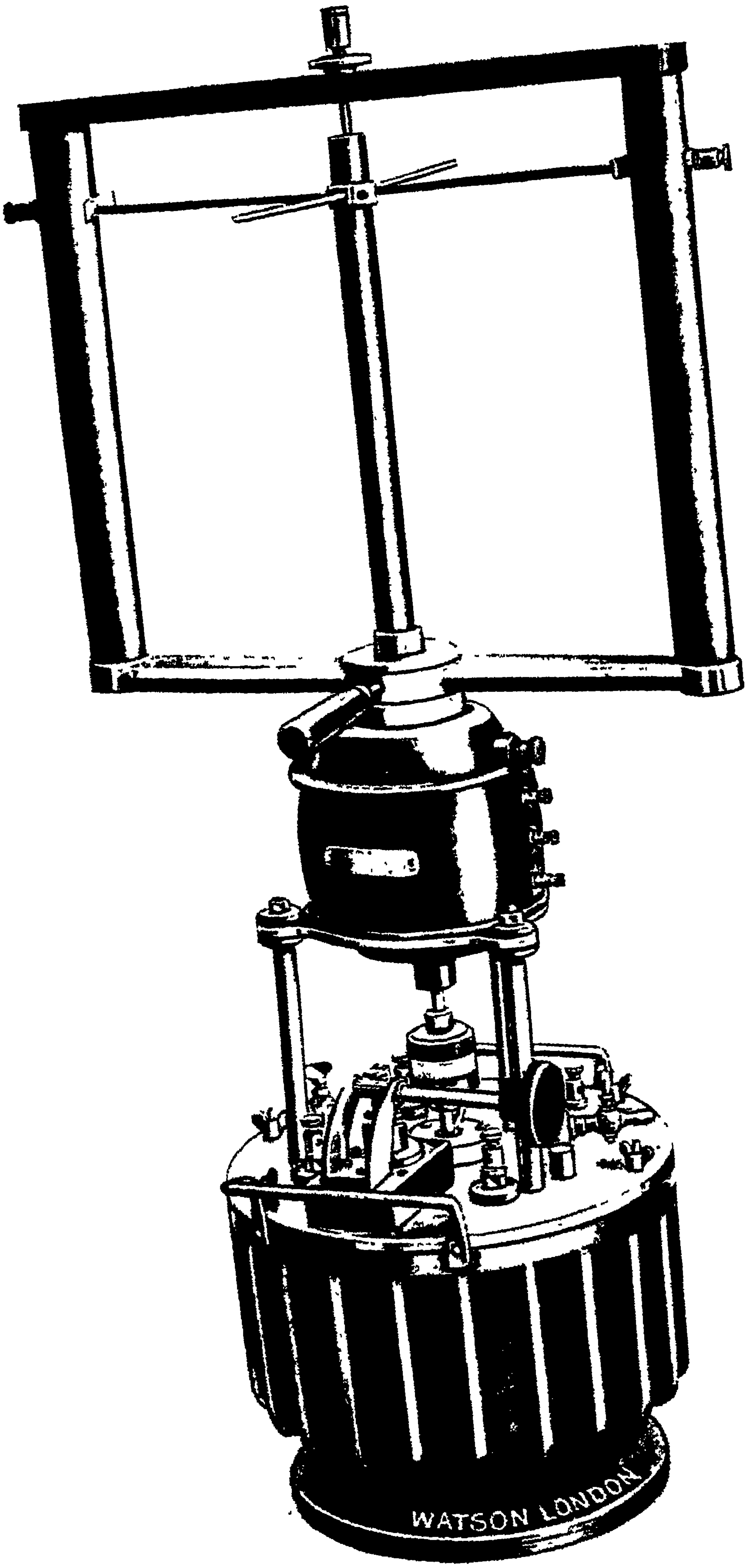



FIG. 233A.—High Tension Selector to prevent Inverse Current.

[To face p. 303.

motor is switched on, it is necessary to have, in the high-tension circuit, some method of telling whether this half cycle gives the correct direction of flow and a reversing device to remedy this, if incorrect. A method for doing this is later described.

The use of this selector in the high-tension circuit, where a more rapid speed of electrode separation is easily obtainable, is in some respects, preferable to its use in the low-tension circuit, where irregularities occur, due to the low voltage being unable to easily and steadily pass between rotating and fixed contacts.

To adjust the relative position of the closing of the high-tension circuit, to the closing of the low-tension circuit in the interruptor, the fixed contacts are capable of rotation about the vertical axis. When these are correctly aligned the maximum current reading is obtained in the secondary circuit. As they are rotated the current can be seen to fall off and when the current of opposite direction is obtained a double-current-reading instrument will show the production of the reverse or inverse current.

Whilst such methods render the use of a coil upon an alternating circuit possible, they are usually unsatisfactory and results compare badly with the same coil, run upon a direct current supply. In all cases the installation of transformer apparatus, more easily controlled and more efficient, would be preferred nowadays when alternating current is available.

Such a device is very useful in a direct-current supply as the fixed electrodes can be rotated so that they only pick up energy in the high-tension circuit at the instant when the voltage is highest and not in such a position that inverse current is present, this being discernible by the high-tension circuit milliamperemeter, as already described. This follows owing to the relative positions in space and time of the high-tension contacts and the low-tension contact.

A very complete apparatus not only to suppress inverse current, by means of switch-gear, but also to aid demagnetisation of the coil core, is the " Rectipulse " apparatus (Fig. 217).

It has often been proposed to utilise the inverse secondary current, due to growth of magnetic flux, by means of switch arrangements, which correctly pass the resulting secondary current *viâ* the X-ray tube.

The objection to all such methods is that, as the growth of magnetism is slow as compared to the fall of core magnetism, the resulting secondary e.m.f. is small and insufficient to give rise, except in very large coils, to useful X-radiation, merely serving to heat harmfully the X-ray tube. In the " Rectipulse " apparatus the utilisation of inverse is approached from the more useful aspect, in which this inverse voltage is added to the voltage of a second coil which, as it is already of such a voltage that useful X-rays are being provided, can usefully, by addition, employ this voltage. At the same time the growth of core magnetism aids the reversed decline of

platinum point becomes surrounded by an atmosphere of insulating oxygen gas and the current is so interrupted. The production of the necessary volume of oxygen under these conditions is so immediate that a nearly instantaneous interruption of the current results.

The break is so rapid in its action that the change of flux in a connected induction coil is extreme, and a high secondary voltage is induced.

The current-carrying capacity of such a cell may be increased by the use of several platinum points as shown in Fig. 235. As the current-carrying capacity is dependent upon the surface area of the platinum point protruding from the insulator, a variation of total current-carrying capacity may be obtained by varying the active platinum surface.

A different view of the action is that, owing to the difference in area of the large anode and small platinum cathode, the concentration of

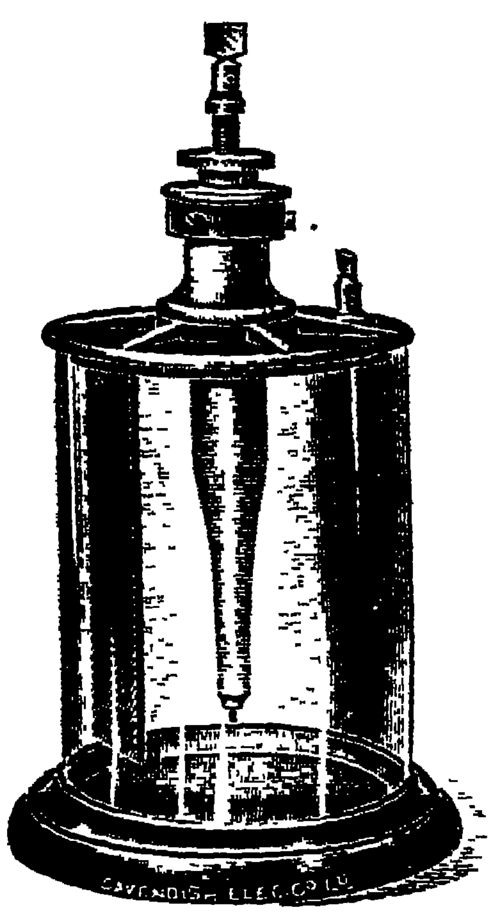


FIG. 234.—Single-point Wehnelt Break.

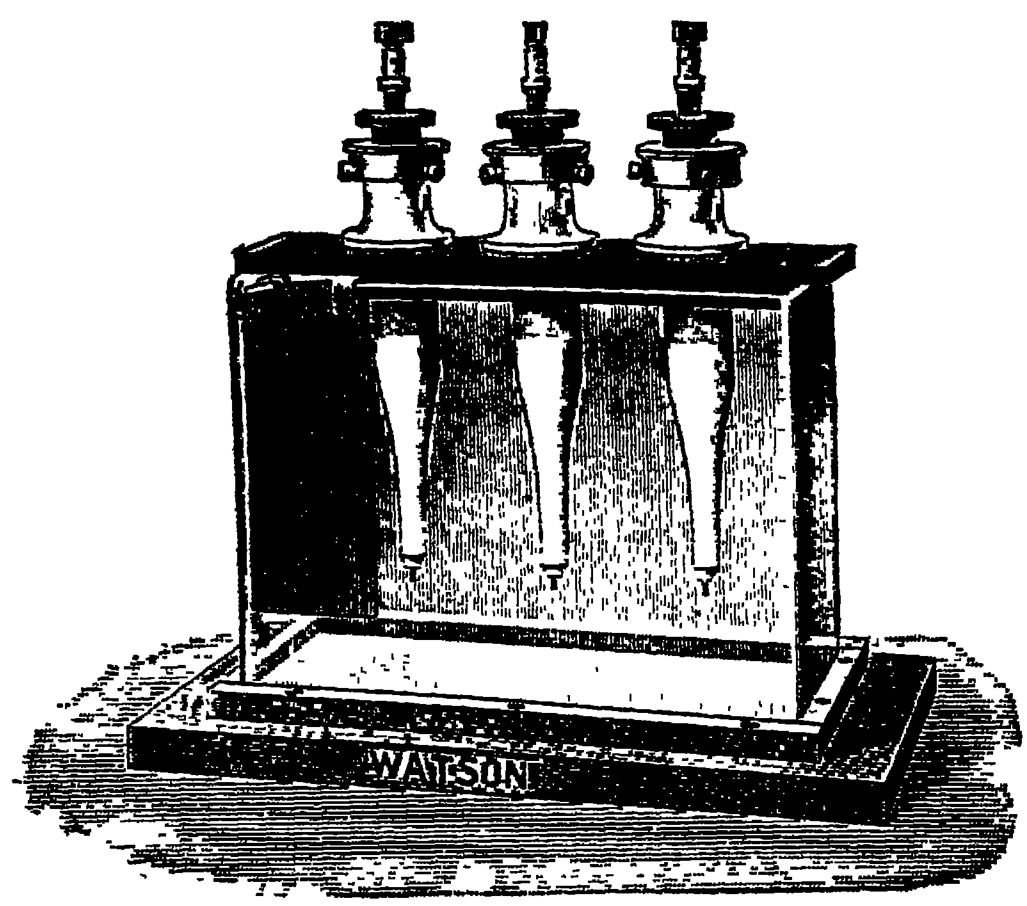



FIG. 235.—Three-point Electrolytic Interruptor.

current flux is so great at the region of the platinum contact that the actual electrolyte is rapidly heated and rendered gaseous and non-conductive, a view borne out by the Caldwell-Simon interruptor.

The frequency of interruption is as high as 2,000 per minute. At such a high rate the action is still steady and the regularity of interruption is better than with a high-speed motor-driven break of a smaller rate of interruption.

No condenser is necessary as in the other forms of break, and this formed the chief support of the Rayleigh theory of the action of the induction coil break condenser.

More probably the explanation is that, to absorb rapidly the energy suddenly applied across the gaseous break such a large value of capacity would be required, that normal values of capacity have no obvious effect

in the apertures already mentioned and not at the electrodes, it is independent of the direction of connection.

A still more modern type of break due to Newman * is similar in form to the Wehnelt, but the anode consists of an aluminium vessel containing the electrolyte, which is a saturated solution of ammonium phosphate. Such a cell forms a well-known type of rectifier for alternating current at low voltages. As a result this break can be used with alternating current as well as direct current and is possibly a better alternative to the mechanical rectifying arrangements used to permit the use of an induction coil on alternating current circuits.

Newman claims as advantages of this interruptor that the current density is only about one-quarter of that of the Wehnelt interruptor. As a result the platinum anode does not so readily disintegrate. Also no objectionable acid fumes are evolved. The secondary voltage is said to have a higher peak voltage (such would be the case if the rate of interruption is increased), the necessity of self induction in the circuit is overcome and the effect of temperature variation is not so pronounced. The time of interruption is shown to be 0·0005 second by oscillographic representation of the action. Newman considers previous views as above of the actual cause of interruption in such cells are not proven.

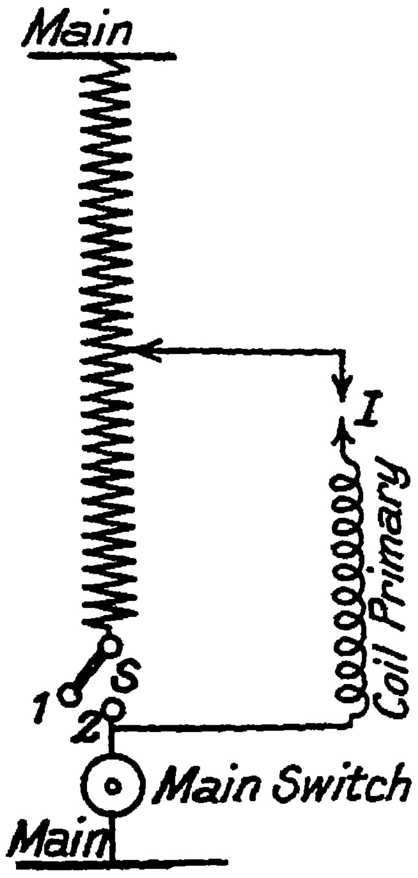


FIG. 237.

*Induction Coil Connections.*—The connections of an induction coil X-ray apparatus are essentially very simple and are primarily as shown (Fig. 237). When the switch S is at position 1 the coil primary is in series with the control resistance, whereas with position 2 the coil primary and resistance are in parallel.

The primary current to the coil is taken from either power mains or more rarely an accumulator battery.

The energy of this circuit will be defined, if we insert a voltmeter V across these mains and an ammeter A to measure the current. This primary circuit will be completed *viâ* the primary of the induction coil and then by the selected form of break I, when this is in its make position.

The mercury motor break being the most common, energy for this motor will be derived at the same voltage from the mains. As these motors are small, and readily start under the small load, a starting resistance is unnecessary, but a resistance in the field circuit, to control its speed, is essential.

A regulating resistance will also be required for the induction coil

* F. H. Newman, *Proc. Roy. Soc.*, 99, p. 324, 1921.

(7) A double-pole double-throw switch to connect the primary circuit *viâ* either ;

(*a*) the interruptor jet circuit ;

(*b*) an electrolytic break ;

the use of two interruptors acting as an additional safeguard in case of breakdown and allowing the use of (*a*) for normal work as screening or of (*b*) for instantaneous radiography.

(8) A dark red pilot light to illuminate the board in the dark and incidentally to indicate the board is " live."

(9) An automatic cut-out, to prevent overloading of the coil, by its automatically breaking the primary circuit is sometimes fitted, and a pair of fuses complete the board.

A suitable switchboard is shown diagrammatically in Fig. 238.

When the small single-pole switch below the main switch is to the left (position S) both the coarse and fine resistance are in series with the core primary circuit. When it is to the right (position P) the coarse resistance is across the mains and in parallel to the core primary and the fine resistance is in series to the core primary.

Two mercury jet interruptors can be used by means of the double-throw double-pole switch to the right, or, when this switch is open, either of two electrolytic interruptors by means of the similar switch on the left-hand side.

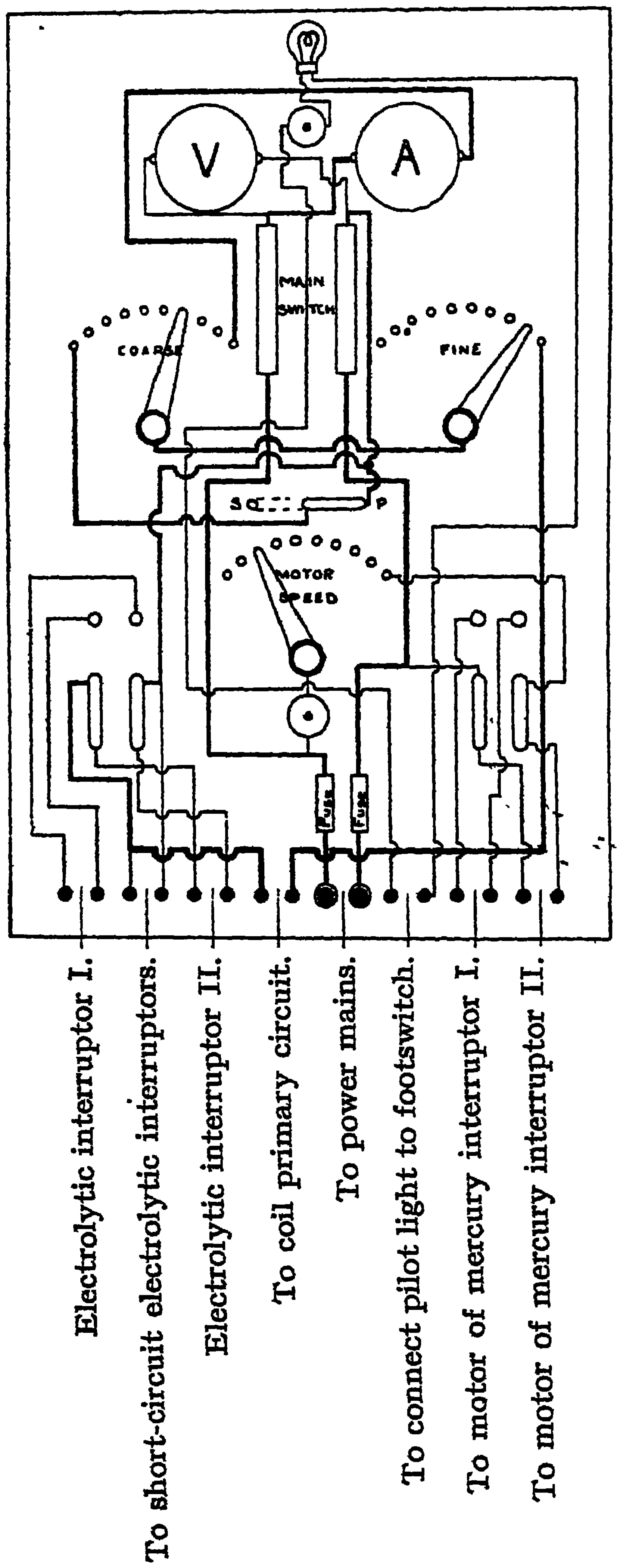



FIG. 238.—Induction Coil Switchboard.

Switchboards may be of the wall or portable type, the portable type only being permitted by Board of Trade regulations for voltages below 250 volts.

The fixed switchboard (Fig. 239) is to the author's mind the best, but requires the services of an assistant, to whom the radiologist calls instructions for the regulation of the voltage, etc. As this may allow the board to

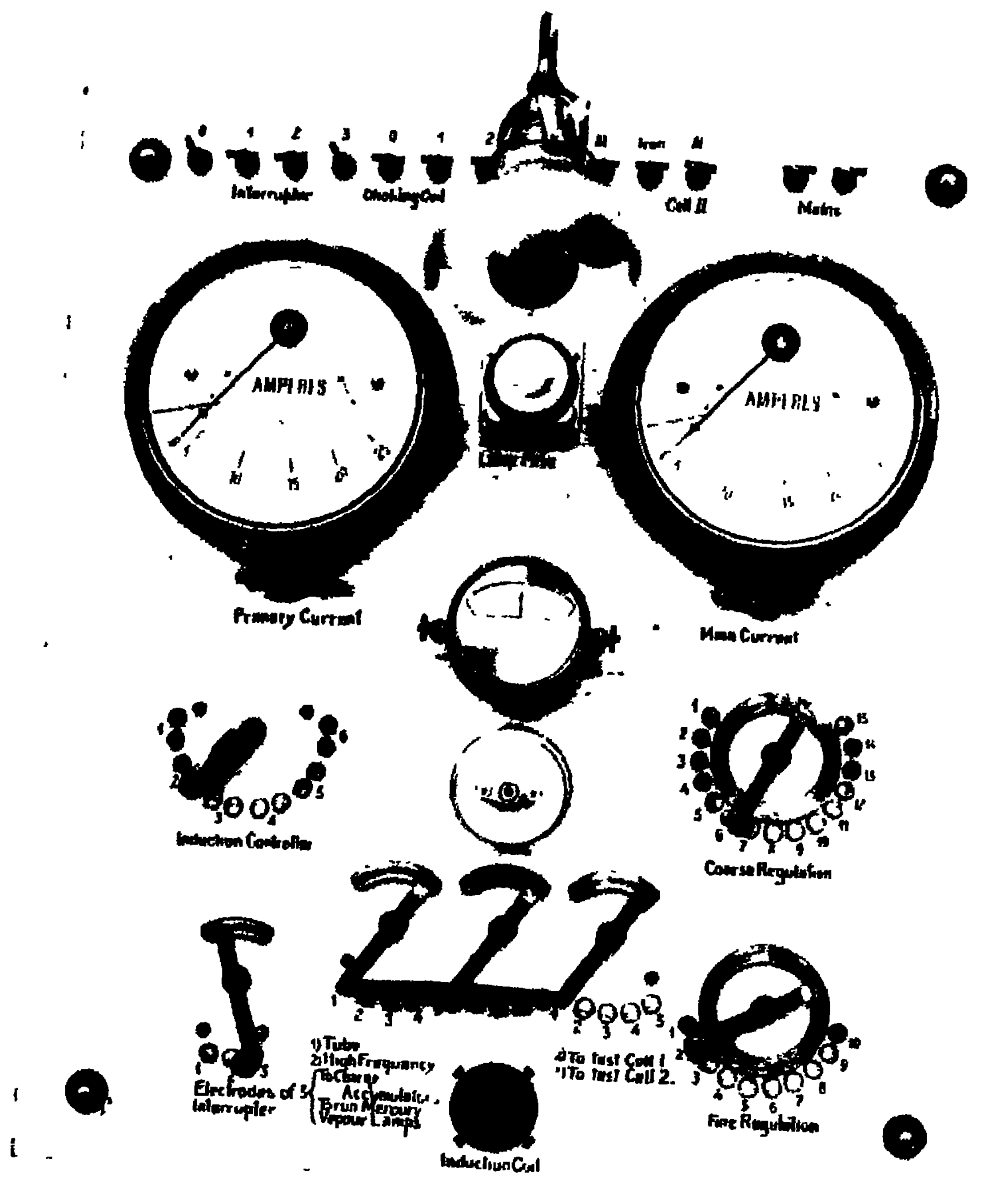



FIG. 239.—Fixed Coil Switchboard (Messrs. X-Rays, Ltd.).

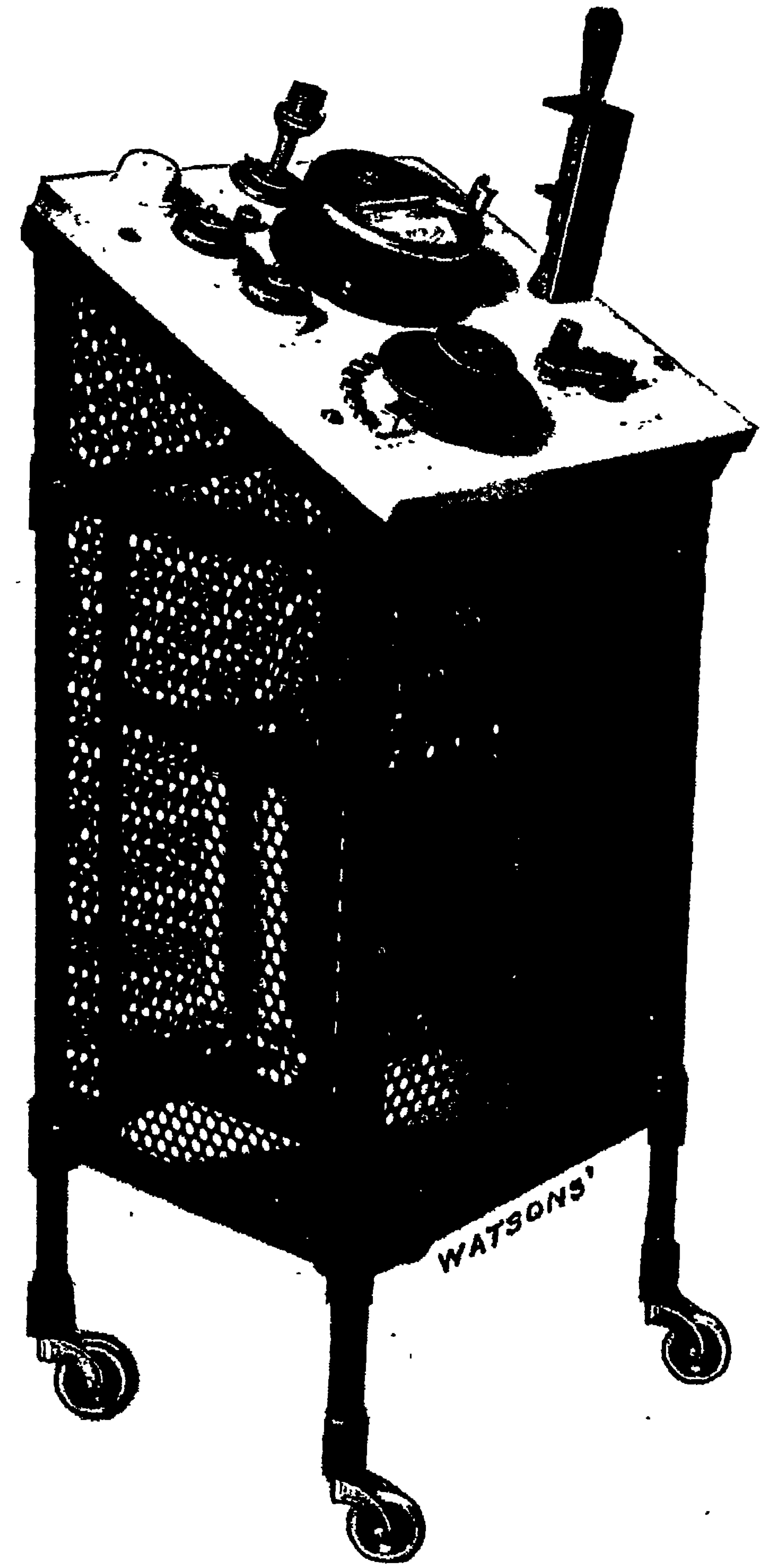



FIG. 240.—Trolley Type Coil Switchboard (Messrs. Watsons).

[To face p. 311.

(2) By means of chemical rectifiers.

(3) By means of high-tension commutating apparatus.

(4) By means of electromagnetic converters, etc., which are only available for comparatively low voltages.

The valve-tube method (p. 343) is a method coming into more and more use to give a " constant current " at high potential and will be more conveniently dealt with later. It bids fair to replace other methods, when electron valve tubes are produced at a more reasonable price.

Chemical rectifiers have not been applied for the specific rectification of high-tension energy and, as the data of the practical use of these is limited, they are possibly of little use.

This however requires research, since the advantage of the more modern Newman electrolytic break, which is essentially a chemical rectifying cell, is that it permits the use of a coil with either direct or alternating current, the latter being rectified by the cell itself.

These chemical rectifying cells consist essentially of a cell similar to an accumulator but in which the electrodes are of aluminium and the solution is a saturated solution of ammonium phosphate.

Zenneck* has used their properties for purposes of frequency multiplication. A reference is given to a paper by Codd,† in which a list of such electrolytes and electrodes will be found.

The most common method of rectification is by means of rotating mechanical rectifiers, used at present in the large majority of transformer X-ray apparatus.

We may differentiate two forms of mechanical rectifiers ;—

(*a*) the disc rectifier ;

(*b*) the point rectifier ;

either of which may take an " anti-corona " type of construction.

It follows that such rectification must be carried out upon the high-tension side of the transformer, otherwise we lose the advantages of alternating current, although a point type of rectifier similar to the induction coil alternating-current interruptor could be utilised, but only at the great expense of efficiency, intermittent pulsations of peak values of voltages being given to the transformer, which would act as an induction coil and be inefficient, as demagnetisation of the core by reversal would not be obtained.

The most simple form of rectifier (Fig. 241), consists of a revolving disc of some insulating material of good mechanical strength (paxolin, etc.) to which are fitted two metallic segments, either of which must be greater than one-quarter of the circumference.

Fortunately in such high-tension rectifiers the current is small and

* J. Zenneck, *Jahr der draht. Tele.*, 7, p. 412, 1913.
† Codd, *Electrical Review*, 92, p. 324, 1923.

Were these segments equal and oppositively placed, an electromagnetic instrument, connected to the slip rings would receive equal and opposite impulses, each segment being alternately positive and negative according to the momentary sign of the slip ring to which it is connected. Owing to the instrument's lag the reading would be zero.

If however the segments are unequal in length, as they are synchronous with the motor current in their variation, the instrument will receive from the long segment a long impulse during one half cycle and, during the next half cycle, a short period impulse from the short segment. Being synchronous the additive effect will be a large impulse in one direction and a small impulse in the opposite direction. The difference will give a steadily maintained impulse in one direction of instrument movement, which occurs when the long segment is of a certain sign. As this disc is fixed in relation to the motor and rectifying disc, the reading allows the instrument to be used to determine the direction of the particular half cycle being rectified. Its pointer is capable of reading in either direction from the mid-zero position. Once its position is ascertained by trial in relation to the secondary current direction, it can be used to determine this and, by means of a change-over switch in the low-tension circuit, the current to the transformer can be reversed, if this is not correct.

To prevent the instrument itself taking a large current from the slip rings it has a high resistance (voltmeter) which may be increased by the insertion of resistance, or better, insertion of self inductance. As the inequality of the impulses renders its readings unsteady, it is not permanently put into circuit, but only (by means of a small switch) when a reading is being taken.

A further form of "phase selector," having the advantage of being automatic, is shown in Fig. 146, Vol. I. This consists of a soft iron horizontally pivoted armature having contacts dipping into mercury cups, *i.e.*, the well-known Pohl reversing switch. This armature has a fixed polarity which is either opposed or assisted by the fields of an electromagnet. The electromagnet is excited by a rectified current, obtained from a commutating device upon the motor shaft, as in the previous type of selector. According to the half wave selected, so will this electromagnet either assist or oppose the permanent magnet. When it assists, it automatically pulls the lever over to make connection in the correct direction, whereas if it opposes, it automatically reverses the lever and direction of current flow.

Below this reverser is a further automatic solenoid release, also actuated by rectified current from the same source. If the half cycle selected is of correct direction of flow, the magnet holds an automatic switch over. If the half wave is incorrect the magnet acts to open the switch, being assisted by a spring control. If the selection is out of step, *i.e.*, the current is alternating, this causes the magnet to no longer

made at their mid-positions, then, if the machine's field coils are in alignment to an armature coil, the disc will be in the position to receive maximum current at one particular cycle the direction of which we can determine by the instrument already described.

If the alignment is such that the disc sectors are between two poles, then it will pass no current at this instant, as it coincides with the zero values of voltage curve.

(2) Practically, by trial and error, which is the best method, as it avoids, in a motor-driven rectifier, the error of the "slip" (*q.v.*, Vol. I.). Since a synchronous motor always lags, or slips, behind the rotating magnetic field causing rotation and this "slip" depends upon the load, there will never be exact synchronism.

If however we make the motor a comparatively powerful one ($\frac{3}{4}$–1 h.p.) this slip, as the rotating disc load is small, will be nearly negligible, so ensuring steady running. The practical method of trial and error for best position, with final permanent fixing, avoids any difficulty due to slip.

The original disc rectifier consisting of a complete circle is expensive, as it requires a large area of insulating material which is necessarily thin and very liable to warp and crack. It is therefore now often replaced by four arms of stouter insulating material as shown in Fig. 244, which have the same function and which avoid the above defects.

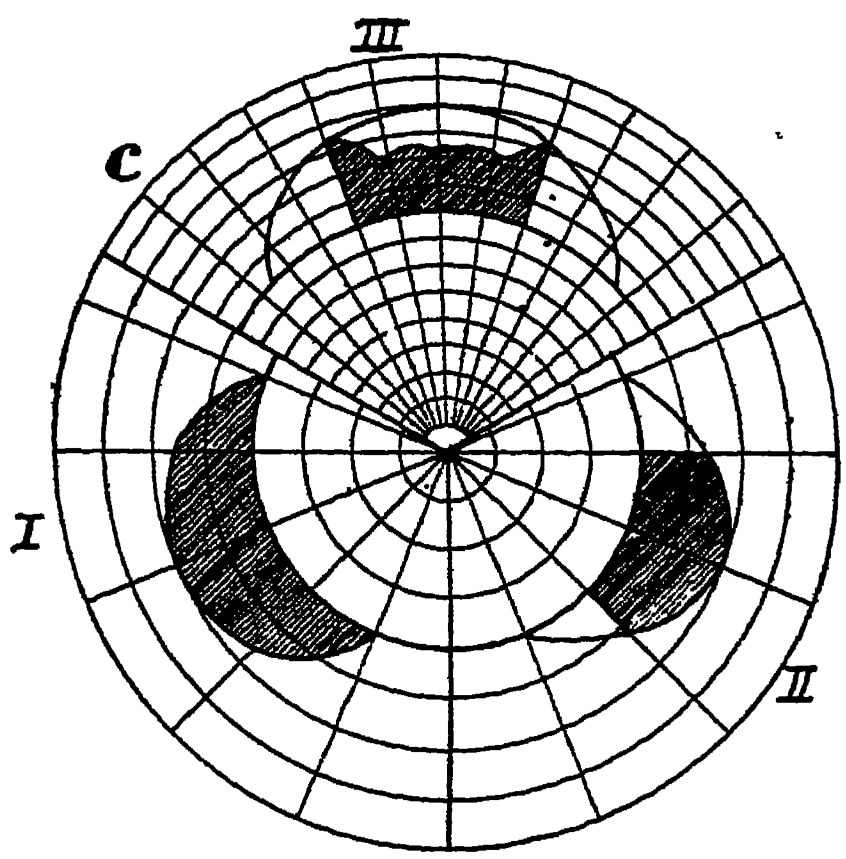



FIG. 245.

If the segments are complete quarter circles the type of discharge, when not on load, is as Fig. 245 (I) when analysed by the Gehrcke oscilloscope. This has the disadvantage that the small voltage component at the beginning and end of each half cycle is transmitted to the X-ray tube. This provides no useful X-ray energy, only serving to heat the tube. The segments are therefore made less than quarter circles, this having the result of cutting out these unuseful softer components and resulting in a type of discharge when not on load shown by Fig. 245 (II).

The type of discharge, when the secondary circuit is put on load, *i.e.*, *viâ* an X-ray tube, is as shown in Fig. 245 (III), which shows the rapid fall of voltage which then occurs.

This is of interest as it is sometimes asserted that our best method of measuring high voltages is by means of an X-ray spectrometer. This type of curve shows us, when the spectrometer is used for this purpose and

when, although the time of discharge will be decreased, only the most useful higher voltage peaks will be utilised.

Such a point-to-plate rectifier is used by Gaiffe, Gallot and Pilon (Fig. 246) in France and by Dean in England. Its rectifying action due to cross connections is more readily appreciated from Fig. 247. It will be seen in one position of the revolving shaft, direct connection is made between transformer terminals and the X-ray tube.

When the shaft has revolved a quarter revolution the connections are now such that the connections between transformer terminals and tube

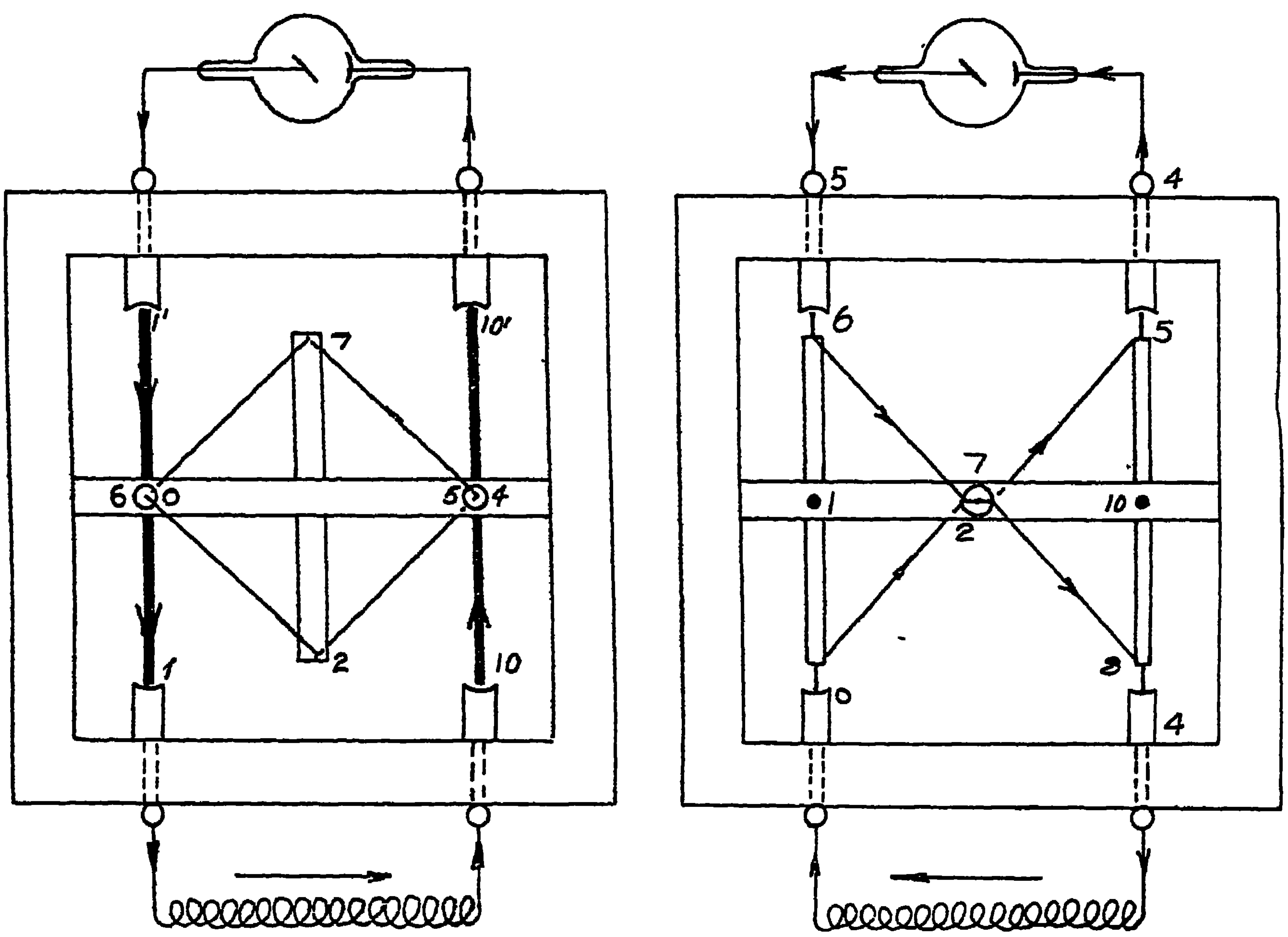


FIG. 247.—Action of Point-to-Plate Rectifier.

are now reversed and the current *viâ* the tube is in the same direction as before.

A very similar type of point rectifier, used in the large "Multivolt" apparatus, is seen in Fig. 267.

*Comparison of Disc and Point Rectifiers.*—Particular manufacturers adopting either of these forms of dischargers claim special advantages and omit the disadvantages.

The point rectifier certainly has the advantage that, if correctly set, a very high peaked voltage is obtained which has special advantages for therapy where it is necessary to remove the radiation due to lower voltage values.

It should however be recognised that any slight error in setting at manufacture or a subsequent error, due to the rotation causing twisting

*Anti-Corona Dischargers.*—The subject of anti-coronaless apparatus has been most thoroughly studied and treated by the American manufacturers who have evolved very satisfactory anti-corona type dischargers.

The action of coronaless apparatus depends upon the elimination of all surfaces of conductors of small radius of curvature.

Whilst it may be argued that such apparatus must have the inherent defects of the disc discharger, it should be remembered that the provision of large flat surfaces is one of the methods of delaying the passage of a spark and causing its rapid quenching (Vol. I.). The discharge of such gaps will therefore depend chiefly upon the distance of the air gap between the electrodes and, if these are suitably chosen, the discharge may occur with great regularity only at the moment when fixed and moving electrodes are directly opposite each other and the selection of the voltage peak may even be as abrupt, and far more regular than with the point discharger.

The American apparatus uses sausage-shaped electrodes, known as "toroids" (from their mathematical form) and good examples are shown in Figs. 244 and 248, the former being a small diagnostic apparatus, and the latter one of the most powerful therapy apparatus.

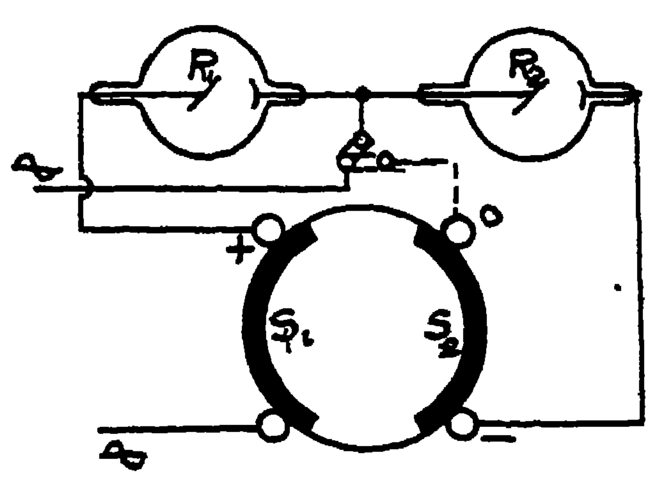


Fig. 250.—Two-tube Excitation.

Fig. 249 illustrates the same principle applied to what we may consider an approach to a moving point and fixed plate discharger. The balls representing the "points" pass between the large flattened spherical fixed electrodes and the discharge is shared with each pair.

*Two-Tube Operation.*—The type of rectifier we have described rectifies every alternate half cycle and sends both half cycles *viâ* a common tube.

Some apparatuses, used for therapy, are so adapted that the "rectifier" no longer rectifies, but merely alternately connects each of two tubes in turn, so actuating two tubes at half the rate of excitation, but allowing simultaneous treatment of two patients, so that energy loss does not result as compared to the more usual method.

Such a high-tension commutating apparatus is more commonly used with higher alternating frequencies, such as 500-cycle energy. The mode of operation easily follows from Fig. 250, if the reader draws the disc in the two possible positions and the direction of the supply reversed for each case.

*Transformer Apparatus, Control and Connections.*—The controls of a transformer X-ray installation may be divided into ;

(1) Control of prime power.

(2) Control of low-tension transformer circuit.

(3) Control of secondary circuit.

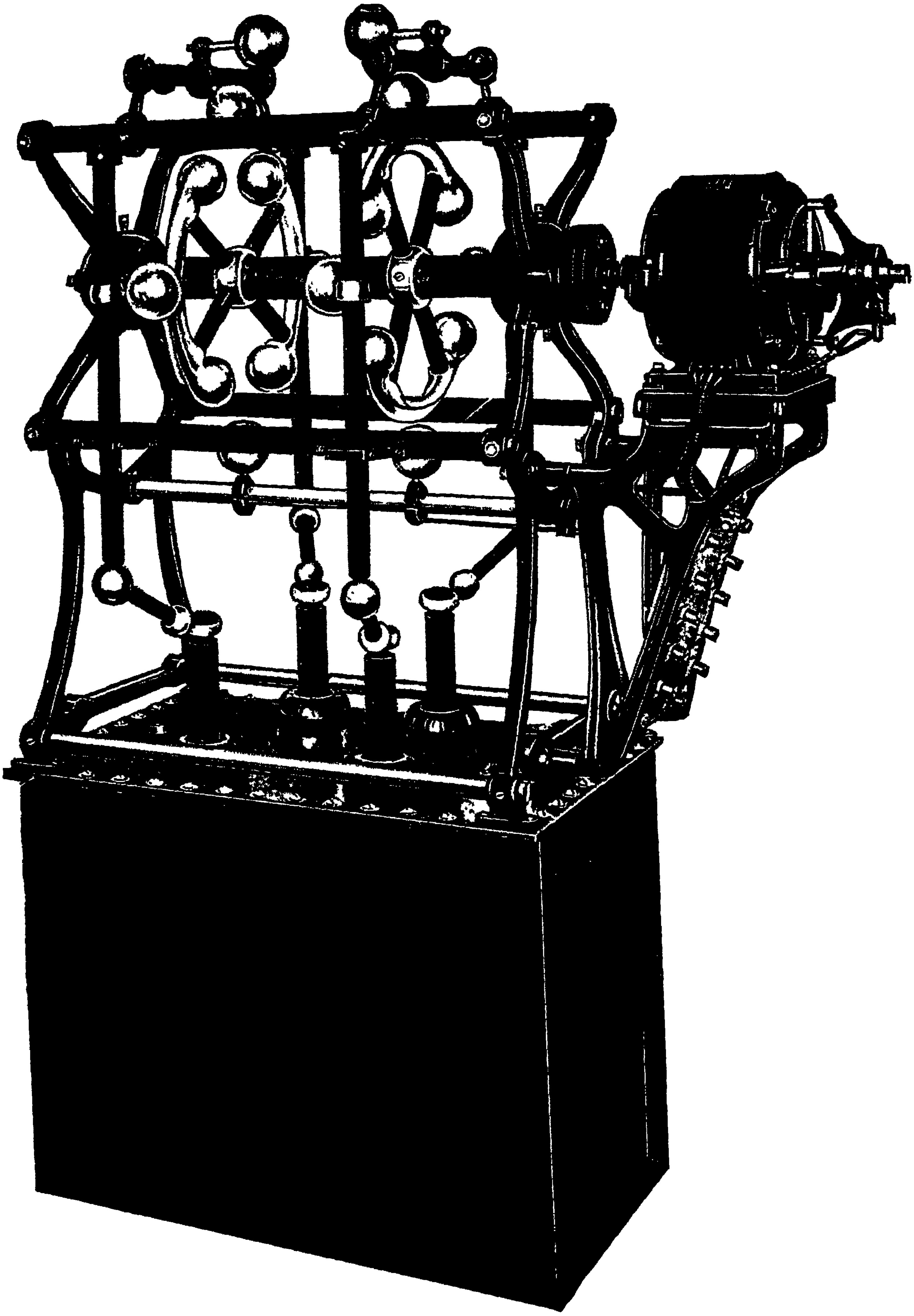


FIG. 248.—Anti-corona Discharger (Messrs. Acme-International Co.).

[*To face Fig.* 249, *between pp.* 320 *and* 321.

(2) Series resistance of about twenty divisions.

(3) Auto-transformer, allowing more efficient control of primary energy in about ten steps.

(4) The low-tension ammeter and voltmeter of the alternating-current source may be conveniently placed upon this board if necessary.

(5) Kilovoltmeter. It would be obviously dangerous to place upon this board any form of high-tension voltmeter. It is however possible to mount a suitable voltmeter which is inserted across the transformer secondary circuit near the earthed mid-point and the actual earth (Chapter VI., Vol. II.). A current will flow to earth at a low potential across the instrument, which is therefore not dangerous. This current will be proportional to the secondary voltage and, by suitable measurement after installation, this instrument may be calibrated in kilovolts.

When electron tubes are used we shall also have, in both induction-coil and transformer switchboards;

(1) Small tumbler switch for the electron filament circuit.

(2) Resistance control of the filament circuit.

(3) Ammeter and, hardly necessary, a voltmeter.

The filament current may be supplied (p. 140);

(1) By means of a step-down transformer in the primary circuit mains, the most easy method when alternating-current energy is available As this filament is connected on one side to the high-tension circuit the transformer must have suitable major insulation and the indicating instrument be in the low-tension primary circuit.

(2) By means of accumulators. This method is dropping out of use owing to the trouble of keeping accumulators in good order, and the need of their periodical charging. As these are connected upon one side to the high-tension circuit they must with the connected ammeter be suitably insulated.

(3) Where direct current is only available a small rotary converter, of not more than 100 watts and even less, is inserted across the direct-current mains. This should give at least 6 amperes at 12 volts, *i.e.*, 72 watts. The smallness of this machine will not necessitate a starter but merely a tumbler switch on the switchboard, which is always provided irrespective of the source of energy. The remarks as to insulation equally apply and the prime energy should, for safety, be applied *viâ* a highly insulated transformer or by an insulating spindle (Fig. 118).

All the connections to this board, if it is of the movable type, should be run from suitable terminals beneath the fixed switchboard to the control table in flexible armoured cable sheathing. Messrs. Dean provide in their switchboard a safety-plug connection in the primary circuit. This may be, at wish, removed by the operator and it is then impossible for any unauthorised person to set the apparatus into operation.

The above comprise all the controls with the exception of the

times the X-ray tube is being broken down. They are obviously easily calibrated to show the actual frequency of tube breakdown.

A pilot light is advisable upon the switchboard, put into circuit by a foot switch, if one is used. If this is a red light it conveniently indicates when the switchboard is alive. A further refinement is some form of time switch with its clock allowing automatic timing of exposures. These times are usually incorrect, but this is of little importance practically. Both time switch and foot switch have a connecting bar which can be shorted across their terminals to place them out of action upon wish.

In all cases the electrical supply company will, at a small charge, instal in the mains a registering wattmeter which allows the total current consumption to be controlled for purposes of estimating the prime costs of operation.

*The Time Switch.*—A time switch is not a necessary accessory for any X-ray installation. Often, owing to defects, they are merely an encumbrance and the operator prefers to depend upon his watch, or some other method as by counting mentally, a somewhat rough method, which however, when the operator is very familiar with the apparatus, is usually sufficiently accurate. Time switches are mainly of two types ;

(1) Clock switches ;

(2) Dash pot (air leak, pneumatic) switches.

Both require some method of automatic break, operated by magnetic solenoids.

The clock switch is very simple. The clock scale is suitably calibrated in fractions of a second and seconds. The hand is set for any desired value of time. A switch of any desired form, actuating a solenoid, then releases the clock mechanism and the hand revolves, until it reaches its zero position, when it completes a local circuit, acting *viâ* the automatic break solenoid, to cause this to break the low-tension supply.

Such switches, for very rapid exposures, of $\frac{1}{100}$ second, may suffer from the inherent defects of magnetic lag. This is of no importance except for X-ray cinematography. An example of such a switch is shown in Fig. 253. Other types of switch are attached to the switchboard by a flexible lead and held in the hand during exposure. Such switches similarly actuate, by a relay circuit, a heavy distant break in the power mains. Longer acting clock switches may be used to control automatically the times of treatment work of greater duration.

The dash-pot time switch (Fig. 254B) is essentially the same in principle as the dash pot mechanism of the Potter-Bucky grid (*q.v.*, Vol. II.). The entrance of air operates a plunger, the movement of which automatically breaks the primary circuit, after an interval determined by the rate of air leak. Exposures of $\frac{1}{8}$ second to 10 seconds are so obtained, and it is stated this method is more reliable than the clock time switch.

wards of the piston will vary, until several holes 30 are reached, when the vacuum is immediately destroyed and springs 24 and 25 pull back the piston and its shaft against the block 19, so releasing the pawl 23, *viâ* 20, 21, and 22, which causes the switch 2 to fly back against 4 and break the previous circuit *viâ* 1 and 17. The elbow lever 11, 10, 12, 13, and the spring system 16 and 18 merely serve for the guidance and easy movement of the piston when it is being set.

To allow use when the time switch is not required, a parallel switch W (Fig. 254B) is provided and, to allow the circuit to be broken, if necessary during a wrongly timed exposure, *i.e.*, at two seconds when the switch has been wrongly set for three seconds, a press valve 31 is provided which immediately destroys the vacuum, and also allows instant exposures of $\frac{1}{20}$ second to be obtained.

A method of obtaining a nearly instantaneous exposure (about $\frac{1}{20}$ second) is by means of an overload relay. Such a relay is shown in Fig. 255, and when an excessive current is passed, as by the current jumping across the spark gap or by an accidental arc to ground, this relay operates in the primary circuit to interrupt the current supply.

As this relay can be adjusted for any given load it is possible to set it for a load less than is actually to be passed. On closing the circuit the relay then operates to break immediately the circuit and so to give a flash exposure of about the above value.

## STABILISERS

When an X-ray installation is operated by a public electrical supply, variations in the supply voltage may occur. Such variations may be due to local causes such as the movement of neighbouring electrical lifts in the hospital, etc., or to distant causes, for example, a supply voltage may change particularly at the time of peak load, owing to rapid variations in the local tramway service.

In the case of alternating current the variation, even with low-voltage apparatus, may tend to be large. Because of the consequences, even in low-tension apparatus, an electrical supply company is compelled, by Board of Trade regulations, to maintain the variations within certain limits. In the case of very high-tension apparatus, as X-ray apparatus, the effect is still greater, even when within specified limits.

For example, if a transformer apparatus is being used with a primary voltage of 200 volts and a secondary voltage of 200,000 volts then a downwards variation of only 1 per cent. of the primary voltage will result in a variation of 2,000 volts in the secondary voltage, applied to the X-ray tube. This will, in turn, cause both a variation of current *viâ* the tube and of X-ray intensity as well as a variation of the quality of radiation, particularly if X-ray fluorescent phenomena result.

the magnet and is capable of adjustment to give the desired current *viâ* the tube.

Assuming a current is flowing *viâ* the tube and magnet A, this current exerts a pull on the armature B, but, if the spring S is sufficiently strong, the armature will not move. If the current is now increased the magnet overcomes the tension of the spring S and the armature moves towards the magnet. The instant the armature moves, the contacts C and D separate and the filament current has to pass through the small resistance R, which then lowers the filament current and so controls the high-tension current *viâ* the tube. This device appears only to deal with a voltage fall, but it appears to the writer that a second similar device would deal with a voltage increase, by inserting a few more turns in the filament transformer secondary winding, so increasing the voltage, if this falls.

The Kearnsley instrument is shown in Fig. 257, in which the series of solenoids can be seen and the most remarkable feature is the long calibrated insulating handle, to allow adjustment of the spring S to any desired value during operation.

A difficulty with the electron X-ray tube is that when the filament is actuated by means of a filament transformer, this is connected across the supply mains in parallel to the main high-tension transformer. When the latter is thrown on load its low resistance primary then reduces the current *viâ* the higher resistance filament transformer. In consequence, to maintain a sufficient filament temperature and electron emission, the filament must always be overheated to the detriment of its long life. To avoid this Siemens use a " compensating transformer." This is inserted with its primary in the main transformer primary and its secondary in the filament transformer primary.

When the main transformer is put on load current passes *viâ* the compensating transformer primary, and the resulting secondary electromotive force is added to that of the filament transformer primary. As a result the heating of the tube filament and resulting electron emission is increased when the apparatus is on load, but when the apparatus is not on load the filament current and heating is automatically reduced to the benefit of the filament life. The degree of compensation can be adjusted to requirements by means of sliding choke coils on the compensating transformer core.

# CHAPTER VII

## THE GENERATION OF HIGH POTENTIAL ELECTRICAL ENERGY

FOR X-ray purposes we require, at least with the present form of X-ray tube, a high potential unidirectional discharge, which may be either maintained or continuous, or may be intermittent in nature.

To obtain such a unidirectional potential the means at our disposal are ;—

(1) High-tension batteries.

(2) Use of capacity switching arrangements.

(3) Direct excitation of direct-current energy at high potentials, by dynamo-electric generating machinery of normal type.

(4) Special electrodynamic machinery, dependent upon the use of rotating magnetic fields.

(5) Influence machines of the Wimhurst type.

(6) An induction coil and interruptor.

(7) A high-tension single-phase transformer with rectifying arrangements, either a rectifying disc or valve tubes.

(8) A three or other polyphase transformer with mechanical or valve rectification.

(9) Higher frequency electrodynamic machinery.

(10) " Constant current " methods in which the high-tension energy, generated intermittently, is stored in a condenser and delivered continuously.

(11) Excitation by means of true high-frequency energy.

(1) *Use of High-Tension Batteries.*—To the medical radiologist this is of theoretical importance only, this obvious method being limited to certain physical determinations, on the score of ;

(*a*) Prime costs of such a battery which must be made up of single cells, of either the primary or secondary type.

(*b*) Expense of insulating efficiently such a large battery, covering a considerable floor area.

In America, a 40,000-volt accumulator battery of this type has been used by Blake and Duane* to determine exactly the voltages at which certain characteristic X-ray spectral lines are emitted and,

* *Phys. Rev.*, 9, p. 571 (1917) ; 10, p. 624 and 697 (1917).

As the voltage is dependent upon this relative motion of fixed and stator coils, we can increase this velocity by increasing the dimensions of the apparatus, whilst maintaining the same velocity of rotation of the moving part. If the exciting coils are rotated, assisting the better insulation of the fixed high-tension coils, we are able to make the dimensions of the rotor much greater and of greater mechanical strength, but a practical limit is soon reached in the region of 10,000 volts, when a large output is being obtained. At lower outputs the necessary energy of mechanical rotation of such large masses for small electrical energy production soon makes the method impracticable.

Impetus to the need of low power, but high voltage, generation of direct current has been obtained by the need of such energy for valve wireless transmission. Other than the difficulties of rotation the greater difficulty of suitable commutation occurs, since the rotating part must be the coils, in which the direct-current energy is produced. Progress has however been made and, in terms of normal electrical engineering, high voltages have been obtained with reasonable safety and good efficiency. In terms of X-ray engineering such voltages, of a few ten thousands of volts at the most, are useless.

We may therefore say that the excitation of low-energy high voltage power for X-ray purposes is economically impossible in the normal type of dynamo-electric generator (but see " The Transverter ").

It has always appeared to the writer that a direct-current dynamo-electric machine at, say, 10,000 volts, quite practicable, could be combined with the Trowbridge method, the parallel and series switching of the condensers being obtained by suitable automatic commutators, giving any desired voltage of unidirectional discharges. The practicable difficulties are considerable, but do not appear to the author insurmountable. Very high voltages should so be obtainable economically.

(4) *The Transverter.*—This modern machine* is of the electro-magnetic type, is due to Highfield and Caverley, and has been commercially produced by Messrs. The English Electric Company, not for X-ray purposes but of much greater outputs for commercial electrical transmission.

The greater economy of production of moderately high-tension alternating energy by the high-speed turbine generator and its ease of transformation to any desired voltage is leading to the gradual displacement of the older direct-current electrical systems, the energy of which was provided by less economical slow-speed reciprocating engines, for which lower voltages were necessary.

The desire to transmit such alternating energy over large distances led, owing to the economy of the copper conductors, to the transforma-

* *Electrician*, 92, p. 567, 1924. *Engineering*, 117, p. 563, 1924.

We have indicated (Chapter V., Vol. I.) that, by appropriate connections of the secondary circuits of transformers it is possible to multiply both the primary circuit phase and frequency in the secondary windings.

The three-phase energy is therefore passed through six three-phase transformers, each limb of any transformer carrying two secondary coils, one connected in reverse connection to the other. The selection of a three-phase primary energy is merely to enable six such transformers to be used. With single-phase energy, eighteen such transformers would be needed to give the same phase multiplication.

The result of this grouping of transformers is to produce thirty-six distinct phases of energy, evenly spaced in time and separated by ten electrical degrees.

We have seen in Chapter V., Vol. I., that, if we apply a polyphase current to the stator windings of an alternating-current motor the effect is to produce a rotating magnetic field upon which the rotation of the magnetic rotor depends. If now each end of these thirty-six distinct single-phase currents were led to a commutator, assuming, as is the case, they are balanced, *i.e.*, all of the same energy, voltage and frequency, there would be an invisible but demonstrable voltage variation, passing round the commutator segments in synchronism with the actual magnetic variations in the transformers which, if each phase was symmetrically grouped around a stator coil, would be effective in producing rotation of a suitable armature.

We however deal with the voltage change at these commutators, to which, if we applied a stationary pair of brushes leading to an external circuit a current would flow by virtue of the revolving voltage, in turn due to the revolving magnetic field.

These brushes would receive in the time of each cycle, *i.e.*, $\frac{1}{50}$ second, thirty-six different impulses, *i.e.*, an impulse every $\frac{1}{1800}$ second, all impulses being of the same direction, since, relative to the fixed brushes, the direction of movement of the magnetic field is in one particular direction.

We have therefore the equivalent of a direct-current generator, except the rotation of the magnetic field is produced by a stationary system of transformers, to which any desired degree of insulation may be conveniently given, which is not the case of a rotating system of armature conductors, as in a normal direct-current generator.

A stationary pair of conductors would only show a steady voltage, equal to that of any transformer secondary circuit in which the thirty-six impulses would be equivalent to a practically steady voltage, as may be appreciated if we go through the somewhat laborious task of equally spacing thirty-six alternating-voltage half cycles between a length representing the time of one complete revolution, *i.e.*, $\frac{1}{50}$ second, the

alternating three-phase variation in the reversed transformer primary circuit. We are then at liberty to use the magnetic changes to which this variation is due, to produce either a single, any polyphase, or direct current at low voltages.

It should be noted that we also partly avoid the insulation difficulties of higher frequencies since such insulation has not to rotate, and actually it is possible to change the frequency by suitable transformer connections.

It is to be expected that the large X-ray installation of the future will consist of such an apparatus of large output (in X-ray terms of energy values) which is led to a suitable high-tension transmission system, from which energy is taken for any particular tube. The operation of a large number of tubes for multiple treatments would, with the increase in their number, not have the serious defect of overloading the remaining tubes and causing breakdown, when any particular tube breaks down, which is the risk of present multiple-tube installations.

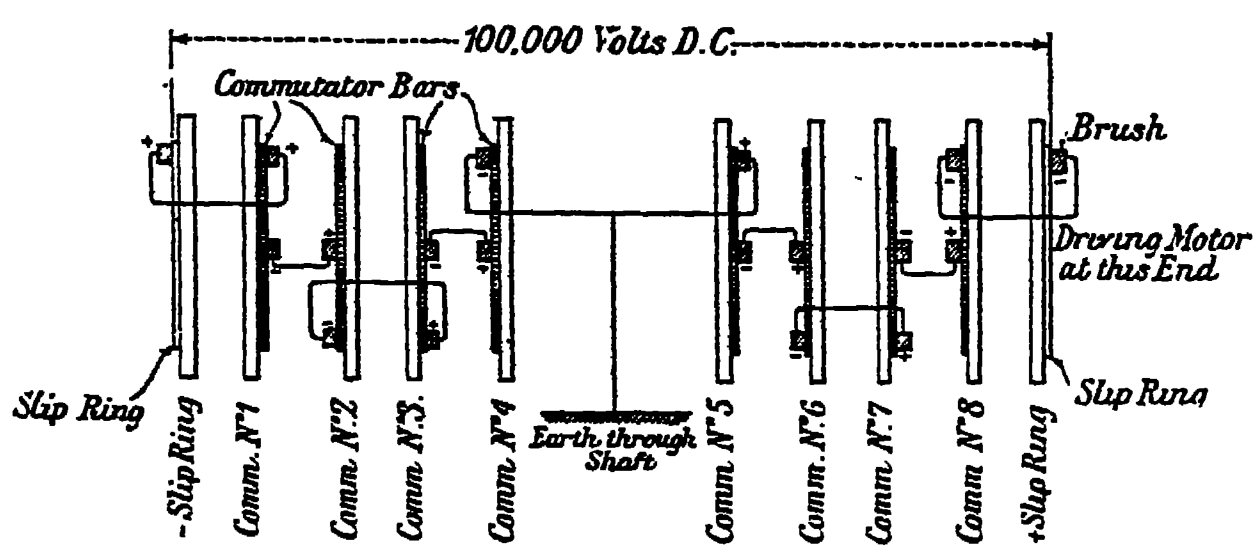



FIG. 261.—Connections of Brush Gear of Transverter.

We illustrate (Fig. 259) the actual transformers of one of these machines, in Fig. 260 the rotating brush gear driven by a motor seen to the left of Fig. 259, within the commutators shown in the centre field of the same illustration.

Fig. 261 illustrates how these commutators are connected to each other and the earthing of the mid-point, for advantages of insulation already described elsewhere (Chapter IV.).

(5) *Influence Machines.*—Influence machines of both the Holtz and Wimhurst types were largely used in the early days of X-radiology. Except for occasional experiments, they appear to have entirely dropped out of use. Whereas for low energy values they could compete with the low energy induction coil, the increasing favour of the transformer over the induction coil for heavier outputs, has indirectly diverted attention from influence machines to which the transformer is much superior,

companies, who however, with less erratic methods of high-tension production at their disposal, are very unlikely to consider it as a profitable line of research.

An attempt has been made by A. E. Dean in his "Ergos" static machine (Fig. 262) for X-ray purposes, to base the design upon sounder mechanical principles of construction. He states that for proper development of the total voltage all the plates should move synchronously. This is not the case in the common type of machine driven by belts, where a different value of slip may occur for every plate and the retarded plates reduce the energy of other plates. To overcome this, Dean uses a lubricated chain and sprocket drive, shown in Fig. 263, where the plates are dismounted.

Dean claims the output of a machine in ergs is the product of plate area times the velocity of the plates in centimetres.

The machine is exceptional in that the plates (Fig. 262) have no sectors. The actual action is somewhat difficult to elucidate and is possibly air friction. Dean states the voltage available is dependent upon the plate radius or, to allow for losses, 80 per cent. of this value. The brush gear is shown in Fig. 263.

The machine is motor driven. An increased efficiency of 50 per cent. is claimed over other types of similar dimensions.

As already mentioned information of higher power machines is scanty, and most of the literature is distinctly of an amateur type.

Hulst in America appears to have constructed a machine giving a current of 20 milliamperes *viâ* an X-ray tube. To avoid danger of the high speed of revolution used for the machine this was placed in a pit. A further machine, used by Villard and Abraham, gave 3 milliamperes at 320,000 volts, *i.e.*, a value suitable for deep therapy with modern tubes.

Some of the most important physical research has, in the early days of radiology, been carried out by such machines, particularly by Dauvillier. As a result of his observations Dauvillier came to the conclusion the discharge *viâ* an X-ray tube, with a constant maintained potential as with the influence machine, was unidirectional but intermittent in character. Recently Moore, using the Transverter, with a very large energy reserve, has shown this not to be the case. The result of Dauvillier was due to intermittency, owing to the machine used by him, of low energy value, having insufficient energy reserve to maintain the discharge which therefore fluctuated, not by an inherent property of the X-ray tube, but merely because the available energy having been utilised, time had to elapse to allow the regrowth of the high-tension energy to a suitable value.

It is usual to drive such "high-power" influence machines by means of an ordinary electric motor, but the relatively great energy produced by hand power leads one to wonder, whether, with improved design, such a

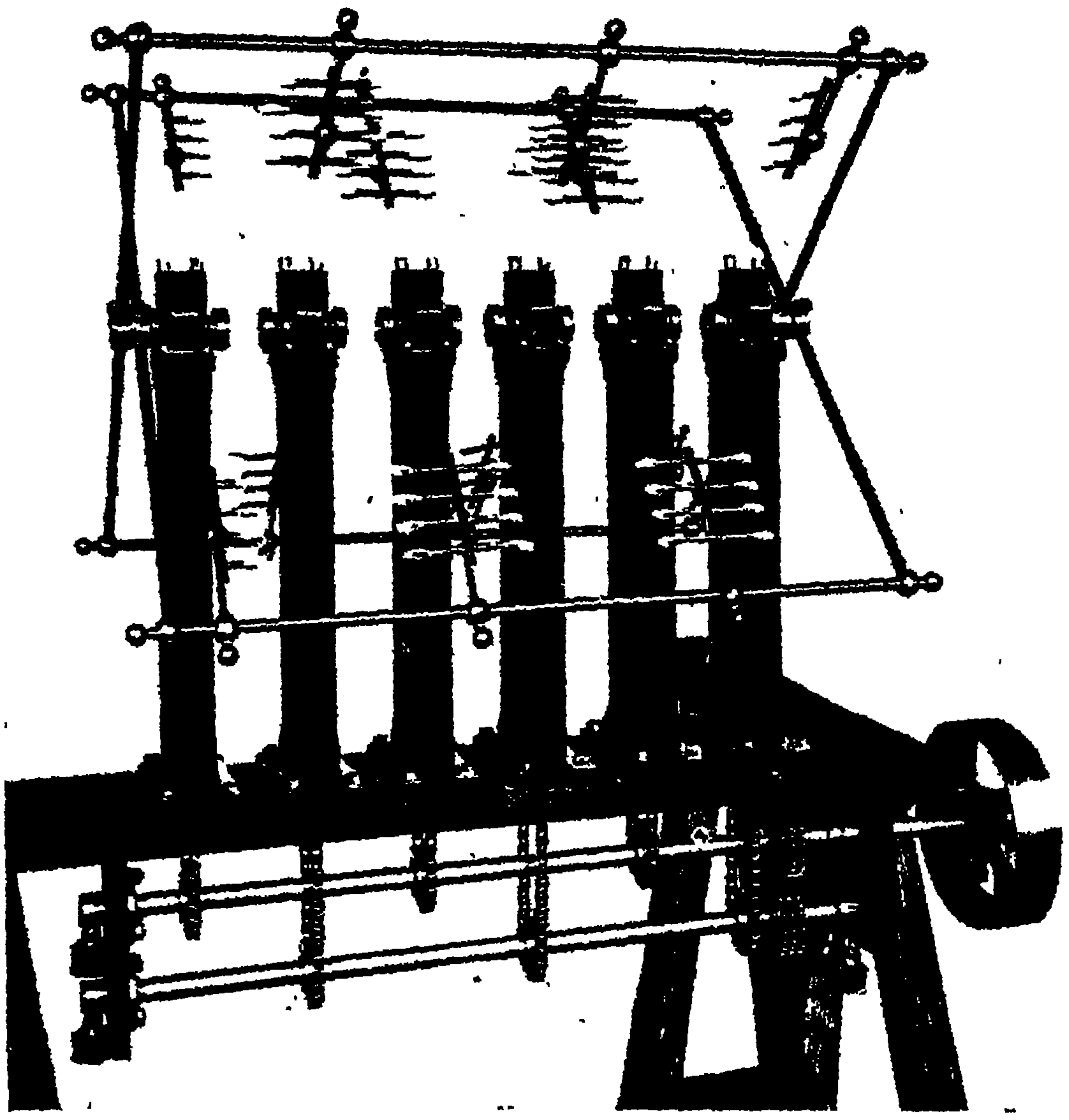


FIG. 263.—Driving Mechanism of Static Machine (A. E. Dean).

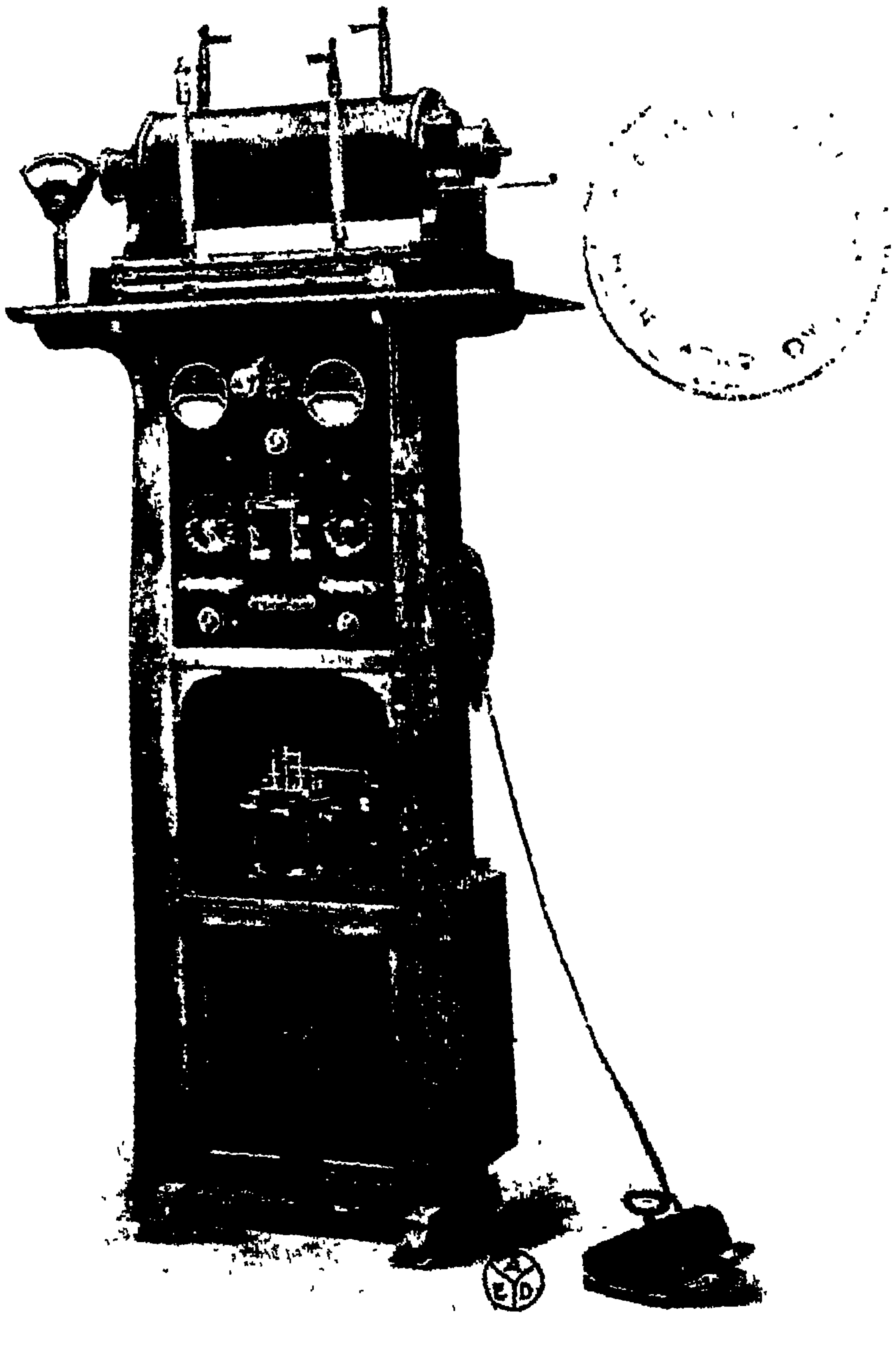


FIG. 264.—Small Coil Installation (A. E. Dean).

[To face p. 339.

of wire, but nearer the centre, where the electrostatic strain is least, there are some four or five layers to a section. If the entire transformer consisted of one layer winding, it would become unduly large, and if several layers were adopted throughout, there might be risk of a breakdown.

The revolving rectifier is of the disc type, but is so designed that it makes and breaks at each reversal in four places at once, thus cutting out much of the objectionable lower tension current.

A further example of a transformer installation is shown in Fig. 266.

This unit is designed for both radiography and therapy, and is therefore capable of very large outputs and is at the same time designed to maintain a useful spark gap for treatment The output of the transformer is actually 100 milliamperes at 140 kv. The unit is absolutely complete and consists of a main transformer which is of the oil-immersed type with metal tank and porcelain leading-out pillars.

The high-tension current is conducted through a rectifier with sphere collectors and paxolin disc with metal segments used as the moving part of the rectifier. This disc, in the case of alternating current, is attached to a synchronous motor or, with direct current supply, is attached to the rotary converter, which is a continuously rated 8 kv.a. machine.

The cabinet encloses in addition the small rotary converter and oil-immersed transformer for supplying the current to heat the filament of the hot cathode tube.

The top of the cabinet carries three porcelain pillars, on one of which is situated the milliamperemeter, another carries the amperemeter for the filament circuit, and the third carries the adjustable portion of the spark gap, which is of the point type. The adjustable side of the gap is spring controlled with a cord attached for altering the gap, and the distance apart of the points is shown in large figures on the disc which is moved with the cord control.

One side of the cabinet carries the starter and main switch for the large rotary converter, or synchronous motor.

The switch table is of the latest sunk type—polished slate—and is fitted with kilovoltmeter, time switch which may be set for any period from one-tenth of a second to ten seconds, auto-transformer regulation, resistance regulation and press button controls for the small rotary converter for the filament circuit and the filament circuit itself. The filament regulation is also mounted on the table and consists of two discs, both of which are calibrated. The discs are concentric, the lower one giving coarse adjustment and the top one a fine adjustment.

The controlling switch for the unit is of the press-button type, mounted in a relay circuit in connection with an electro-magnetic switch operating in oil. This oil switch makes and breaks the primary circuit.

In addition a foot switch is also provided in the relay circuit and is used for radioscopy.

operate two tubes at 250 kv., the protective cupolas of which (Fig. 268) have been already described (Chapter VIII., Vol. II.). The generating apparatus is installed in a separate room (Fig. 269), the high-tension leads being led directly into the protective cupolas with consequent advantages of this arrangement, dealt with elsewhere.

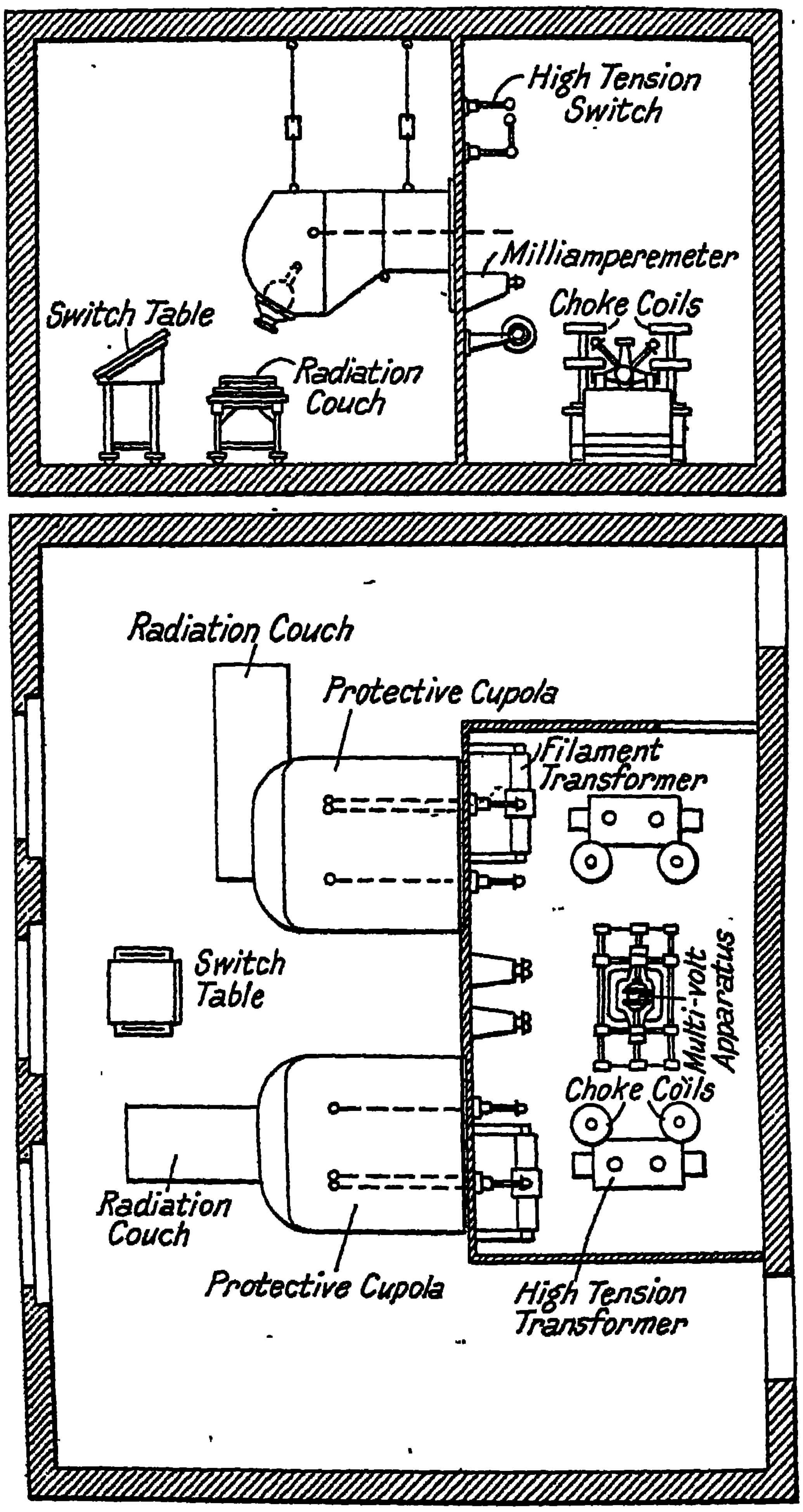



FIG. 269.—Arrangement of Multivolt Apparatus.

The special feature of the large high-tension generating plant is the use of two high-tension transformers in which only the secondary circuits are oil immersed, the closed iron cores so forming a support for each transformer and also facilitating cooling. Each of the two transformers is protected by large choke coils in each high-tension lead, from which they (the leads) pass to their particular point rectifiers, both of which

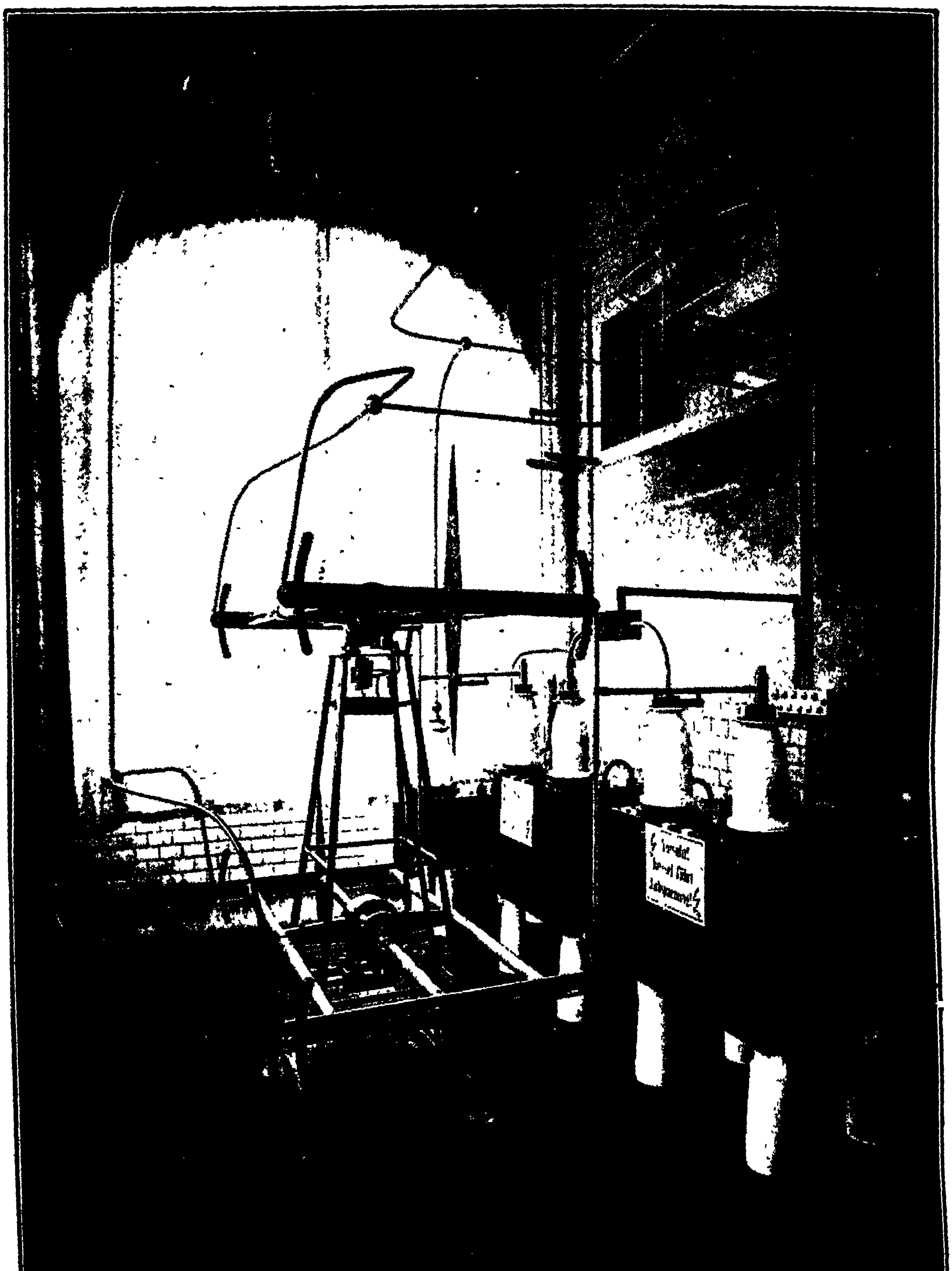


FIG. 270.—Dessauer Transformer Installation (Messrs. Viefa-Werke).

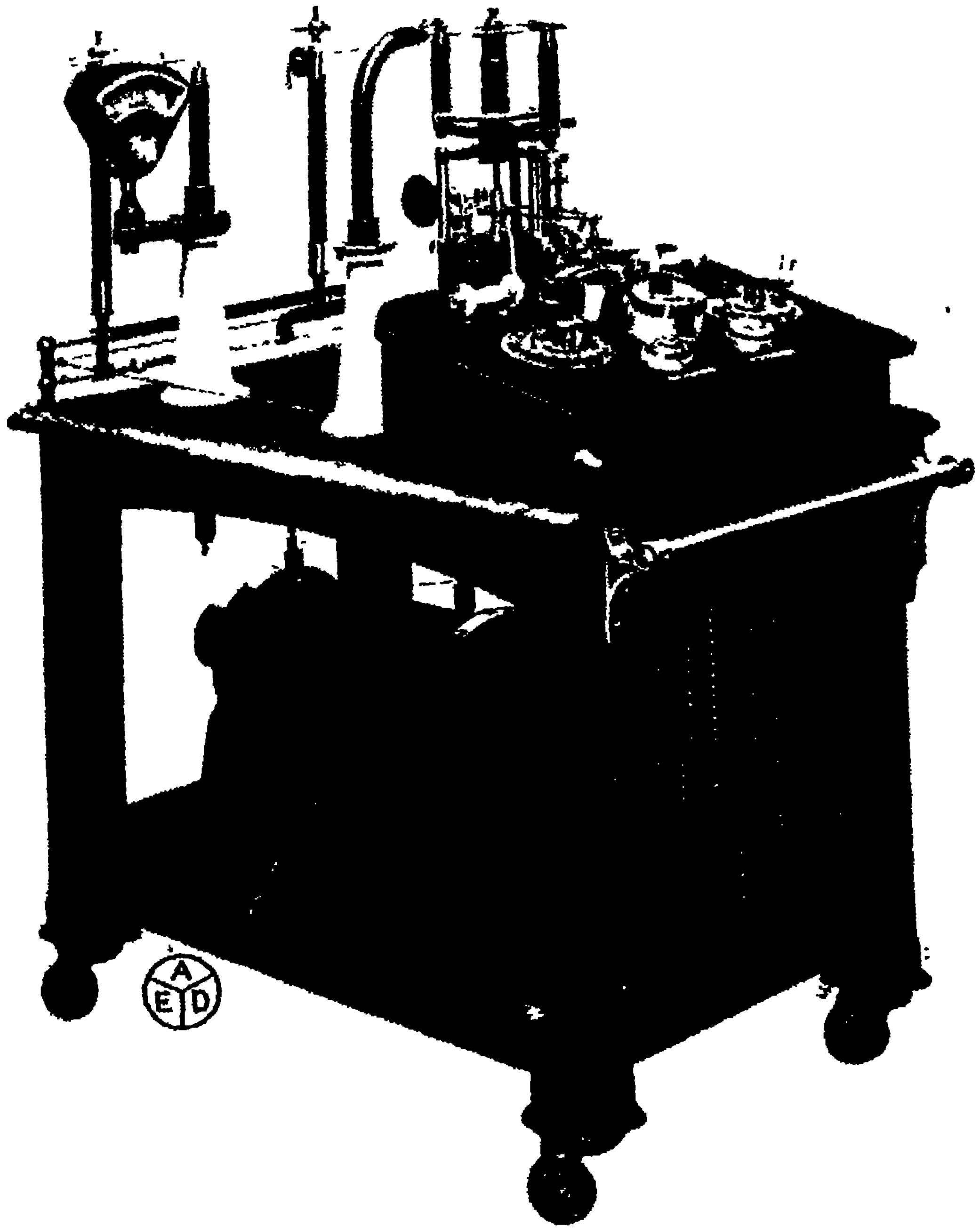


FIG. 271A.—Portable Induction Coil Apparatus (A. E. Dean).

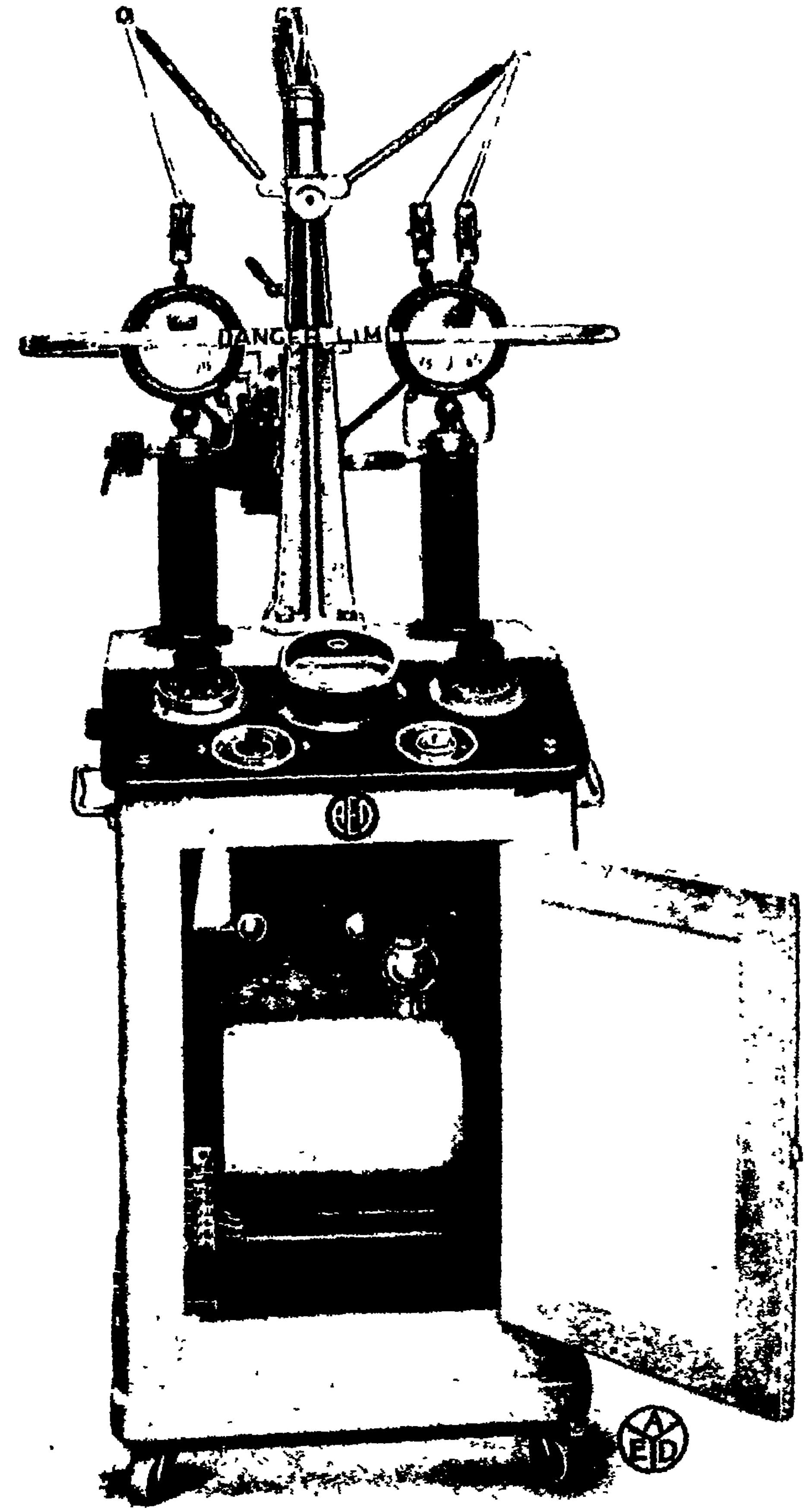



FIG. 271B.—Portable 30-Milliampere Transformer Apparatus (A. E. Dean).

[To face

are arranged so as to only pass current in the particular direction in question.

The chief advantages with such valve tubes are that the rectification is absolutely noiseless, more regular, and injurious nitric oxides are not produced as with the open disc type rectifier. The losses and reduction of transformer voltage is also much smaller in this apparatus, and it is impossible for high-frequency surges to pass back to the transformer windings to their detriment. By means of a suitable low-tension transformer, the installation, having no rotary motor or generator, can be simply adjusted to any varying voltage. The Polydor apparatus allows 40 milliamperes to be obtained at 100 kv. continuously, and 250 milliamperes for instantaneous work, *i.e.*, outputs superior to the normal apparatus having a disc rectifier.

A disadvantage of such apparatus, as compared to the disc rectifier, is that the valve tubes allow much low-tension energy to pass, producing non-useful soft X-radiation, which may, however, be screened out by a

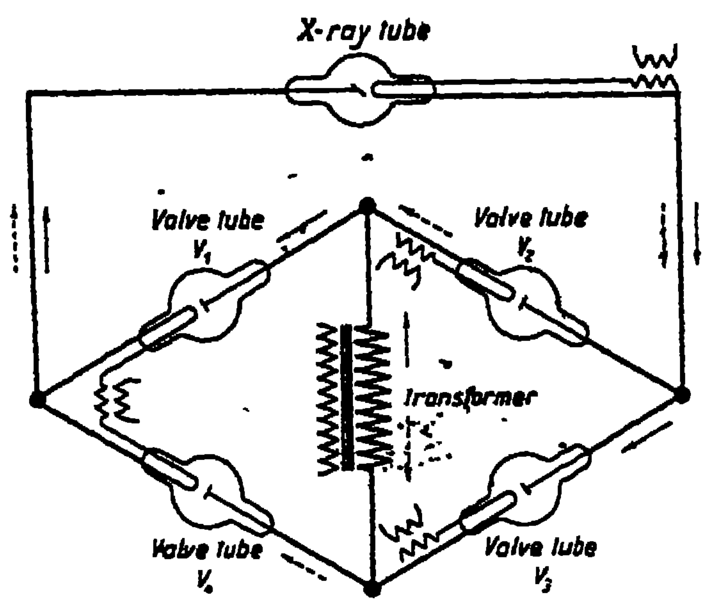



FIG. 272B.—Valve Tube Rectification. (Gratz.)

filter. This method since its earlier use by Villard * with the ionic valve tube, has only been rendered useful for practical operation by the development of the thermionic valve tube. One of the earliest investigators to use valve-tube rectification was Caldwell,† who so rectified three- and four-phase alternating energy.

(8) *Polyphase Apparatus.*—In discussing the direct-current generator (Vol. I., Chapter V.), it was made clear how a sufficient number of equally phased alternating half cycles tended to give an approximately constant current and voltage.

Such a constant current may be considered as the sum of a number of rectified single-phase alternations, slightly different in phase. After rectification of a polyphase current the energy of the X-ray tube, to which it is applied, is represented by the sum of the energies of each of the single-phase components. It follows, if we take the most common form of poly-

* *Jour. de Phys.*, 10, p. 28, 1901.
† *Amer. Jour. Rönt.* 5, p. 567, 1918.

tube, is best appreciated from the diagrams of Fig. 274, where relative values of current or voltage corresponding to maximum values of 100, are given with appropriate signs at the various periods.

It should be appreciated that such a type of rectifier is essentially a rotating arrangement, keeping pace synchronously with the rotating magnetic field due to the primary three-phase voltage. This field cuts the transformer secondary windings in turn, giving a successive difference of voltage at the three leads, which the synchronous disc passes on to the tube, by connecting each lead in turn so that the return circuit, after passage *viâ* the X-ray tube, is *viâ* the other two leads, as in the normal three-phase system.

Correct arrangement of the disc in synchronism with the phases is of importance, as is the point rectifier.

The circuit to the X-ray tube is not directly to the X-ray tube from the fixed contacts, but *viâ* slip rings mounted upon the disc spindle, one lead being upon either side of the disc.

It should be appreciated that the alternative function of the two sectors is in one case, only to connect two high-tension tube leads, the other allowing for the return lead of these two connected leads. One objection is that the sector of such a device must be of sufficient length actually to connect any two leads, *i.e.*, at least have an angular measure of 120 electrical degrees. In a patent taken out, it is stated the segments may be greater than 120 degrees by a value of 60 degrees, this increased length being such, that the additional length follows and does not lead the normal lengths, when differences due to the particular sign of each phase would occur and a potential " inverse current " result.

In the patent * taken out by Donnisthorne of the Cox-Cavendish Company, a point-to-plate type of rectifier is also shown, but these " plates " of sausage form must necessarily be 120 electrical degrees or the return circuit for any particular phase is not made and the action is irregular and intermittent. Such a rectifier is not truly a point rectifier but merely a reversal of arrangement of the disc segmented type.

Whilst the angular electrical measurement must be 120 degrees with a four-pole generator the actual mechanical angular measurement is only 60 degrees.

Until recently this method does not appear to have been much used in England with the exception of the experimental work of Moore already mentioned, who used a rectifier constructed by Messrs. Cox-Cavendish and the installation described below.

Whilst the author has no knowledge of a definite installation, Siemens and Halske, in Germany, advertise an X-ray generator working from three-phase power circuits which may possibly, but not necessarily, be of this type.

* Brit. Patent 218,344/1923.

The potential difference as applied to the tube at this point is represented by the thick part of the line *a b*, and the positions of the rectifier shown at *c d* and *e f* correspond with the lines similarly lettered on the diagram, the horizontal line *h* indicating zero potential.

It will be seen that the rectifier arms pick up the phases of the three-phase supply in such a sequence that the potential as applied to the tube is always of the same sign, but it is not absolutely a constant, because a minute examination of the curves *i* and *j* reveals that the vertical distance between them varies within small limits, the minimum length, corresponding to the lowest potential difference, is at the positions *ab*, *cd* and *ef*, and between these positions the potential difference rises. The resultant is shown by the curve *g*.

In the plant made for the Middlesex Hospital the above arrangement is duplicated, the point *k* on the rectifier shaft is earthed, and therefore the lower curve *j* becomes the straight line *h*, and a second transformer and pair of rectifiers are connected in series. The end of the now earthed rectifier *k* is of course no longer connected to the tube, this latter being joined to *l* and to the corresponding point of the second rectifier.

A method equally applicable would be the use of valve tubes,* preferably of the electron type in place of a rectifying disc, with a three-phase system. Such a method, were valve tubes reasonably cheap, would offer advantages over the mechanical rectifier method. For example, a three-phase system would, by virtue of the rectifying properties of the valves, only allow the passage of any particular phase when the voltage and current were correctly oriented with regard to the X-ray tube. For this particular phase the appropriate transformer winding would be on load and a full load current pass. For the other two phases the transformer circuits would be on open circuit, no current would pass, the chief losses being the small magnetising currents in the respective transformer circuits.

It is only a further step to use in therapy such an arrangement for three-tube working, with a valve tube for each particular phase to rectify the current for any particular tube. With the single X-ray tube arrangement, as each particular valve is operating for its particular phase, the frequency *viâ* the X-ray tube is a threefold frequency. In the three X-ray tube combination we have each tube operating as a single-phase tube of the original frequency.

(9) *Higher Frequency Excitation.*—If we analyse the three-phase method, we see this is largely only a method to operate an X-ray tube at a threefold frequency of that of any particular phase. The advantage from the point of view of the X-ray circuit is that a threefold intensity of X-radiation is given, and providing the tube is dimensioned to allow the use of

* Originally used by Caldwell (see p. 344).

up as a "wattless current." Such a storage is brought about more efficiently and cheaper by means of a single secondary transformer winding in which we obtain a threefold frequency.

Whilst we have shown a valve tube as the rectifying device, we could equally well use a mechanical rectifying disc in the threefold single-phase circuit. The only necessary condition is that its speed of revolution must be three times that of a similar disc in any of the single phases.

Such a disc would be mechanically more simple than three-phase rectifying arrangements.

With electron tubes the X-ray tube and valve arrangement could be replaced by a single X-ray tube and no valve, to give a threefold frequency and approximately threefold intensity of radiation, as compared with a single-phase tube.

We can still further increase the frequency and the approximation to a continuously maintained current by ;—

(1) Use of a higher frequency in the three-phase primary, this merely requiring a greater speed of revolution of the rotor of the existing machine, *i.e.*, whereas with a sixty-cycle three-phase supply an electron tube is broken down $3 \times 60 = 180$ times per second, with a primary frequency of 120 this value is increased to 360 per second and both values are doubled if, by means of a rectifier, each half cycle is used.

(2) By a further stage of frequency tripling as Fig. 278, giving a ninefold frequency so that with a primary frequency of sixty cycles this is now $60 \times 9 = 540$ discharges per second, or, if each half cycle is used, 1,080 discharges per second. Such a frequency would give a rapidly maintained X-ray tube current tending very nearly to and probably more nearly to a continuous flow than the condenser "continuous current" apparatus now coming into use.

Whilst the above method has not been used in X-ray technology, the method has been used in wireless technology. It is quite easy to build alternators of small size to give 10,000 cycles per second by means of the "inductor" type of alternator (Vol. I.).

By use of a frequency tripler this can be multipled to 30,000 cycles per second, or even higher, if desired. At this very high frequency it would be impossible to use a mechanical rectifier, but an electron valve tube would still function if questions of insulation were technically solved.

Such an apparatus would, except for the alternator, have no moving parts and, by the use of specially cooled transformers with oil immersion, high efficiencies of 80 per cent. upwards could be obtained, for the secondary energy, this being the efficiency of similar wireless apparatus.

These methods have not yet been attempted in practice and as far as the author is aware the highest use of mediumly high frequency energy is the 500-cycle "Radio-Silex" outfit of Koch and Sterzel of Dresden.

The limitation of higher frequency energy of high milliamperage is

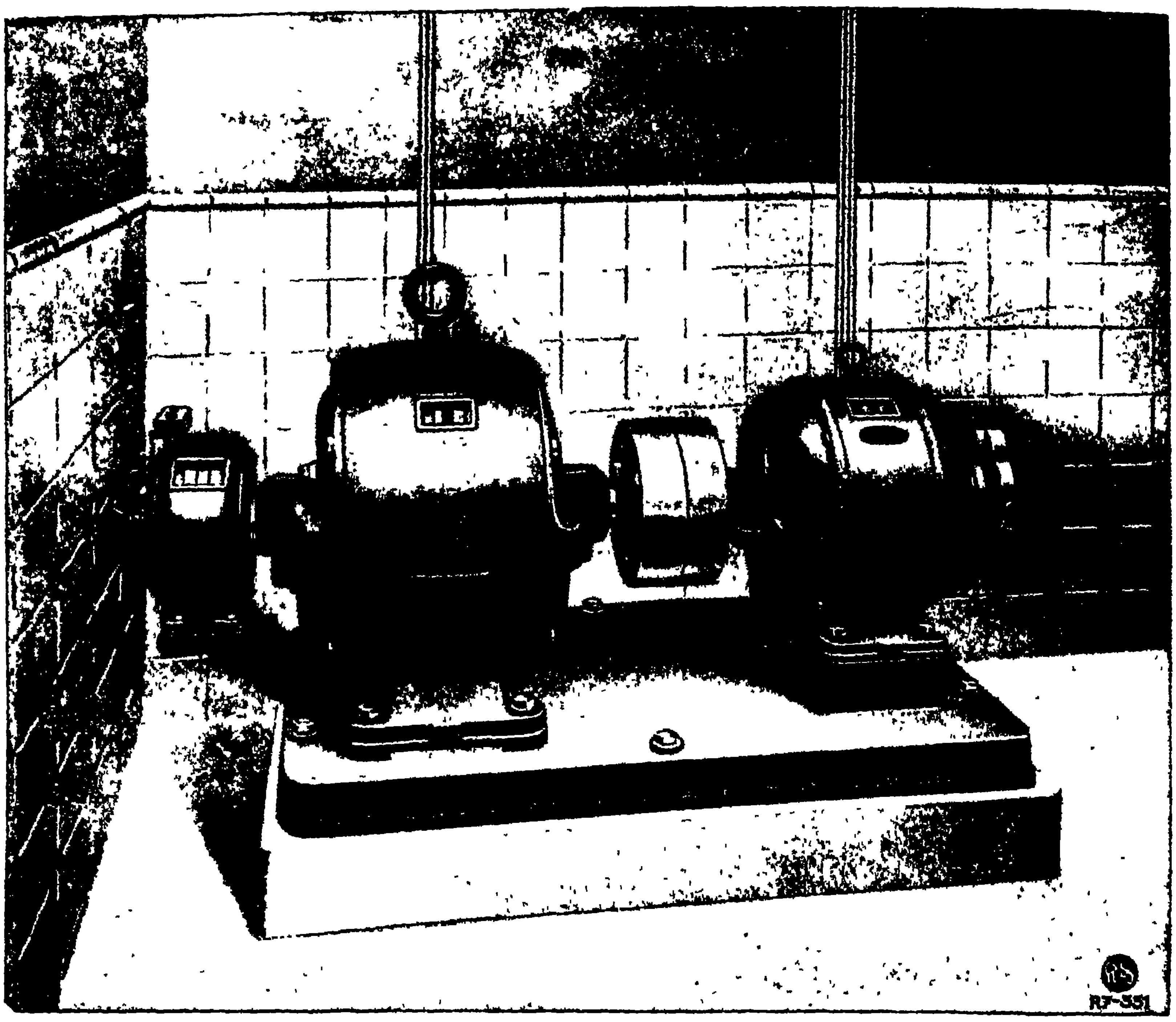


FIG. 279.—Radio-Silex Generating Plant.

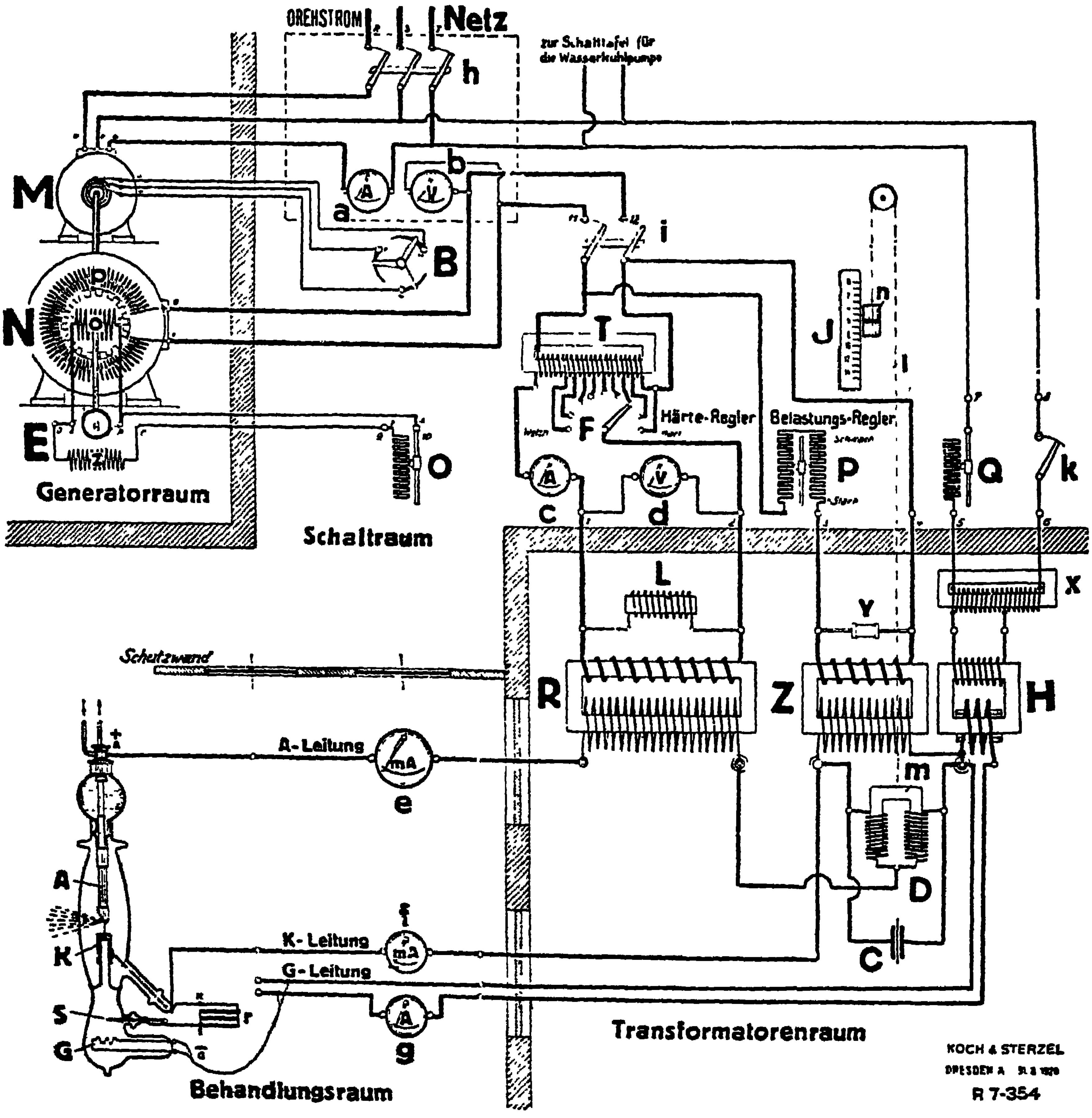



FIG. 280.—Connections of Radio-Silex Apparatus.

[*To face p.* 351.

and hence to the lead of the tube filament G and the other lead to the tube cathode K.

(3) The heating of the filament G is derived directly from the power mains by a circuit closed by a switch *k* and regulated by resistance Q and hence, *viâ* a step-down auto-transformer *x*, giving any desired independent regulation of current and of voltage by Q. The current is 13 to 14 amperes.

This auto-transformer control feeds the tube filament G, the current being indicated by a filament ammeter *g*.

Across the secondary terminals of the " firing " transformer is a choke coil D which serves to connect, at its mid-point, the circuits of transformers R and Z, the choke coil being bridged by a condenser C, so forming a high-frequency device, to allow easy passage of high-frequency surges and to equalise their effect upon R and Z in the same way that the earthing of the mid-point of a transformer serves to prevent one limb driving the other limb. This choke coil is regulated by a counterweight.

We have now considered the transformer system shown in Fig. 281, where the main transformer is seen to the left with protective choke coils on each terminal and the " balancing " choke coil D above. Beside this is the equally large " firing " transformer and, to the right, the filament transformer H.

The whole of the switchgear installed in one room is shown in Fig. 282,

The operation of the Lilienfeld tube is as follows, following an older method of wireless telegraphy, to excite regular discharges.

The filament of this electron tube is heated *viâ* the secondary of H.

Across the anode A and cathode K is applied a high potential from the transformer R.

Electrons emitted from G are controlled by a " grid," across which, *viâ* a high regulatable resistance *r*, an electrode S, actually a rod, receives an alternating charge, so serving to regulate the emission of electrons from G by a space-charge effect, since the potential of S will serve to overcome the space charge (*q.v.*, Vol. I.) by a degree first dependent upon the voltage of S (and K) and secondly upon the dimensions of the rod S. Owing to the great electron emission from G (operated at 13 to 14 amperes) the space-charge effect would otherwise be considerable.

The electrons from G are then accelerated between G and K by the potential of the firing transformer Z which, by its periodical reversal of direction, in one half cycle prevents the electron emission from G, and in another half cycle, aids it. As this voltage can be exactly adjusted and its secondary circuit tuned by D, a very regular series of electron emissions can be obtained.

Electrons during the half cycle which aids emission acquire, between G and K, a high velocity and are, by the form of electrode K, concentrated to a fine pencil, which then experiences the great potential across K and A,

and actually, as Moore found for the three-phase method (Fig. 275), a practically continuous value of voltage, and hence of emission, is obtained.

The great advantage of a continuous emission is, the same voltage being always applied between anode and cathode, all the electrons, particularly from a hot cathode tube, tend to acquire the same average velocity and to emit a more homogeneous radiation of constant wave-length and penetration.

Further, the applied voltage being sufficient, since the voltage is always constant, the efficiency is greater as we do not have so many lower speed electrons giving unuseful radiation ranging from ultra-violet radiation, light, heat to high-frequency surges.

The ideal type of voltage for X-ray excitation would therefore be a constant direct high voltage, but we have seen there are difficulties in the direct electromagnetic generation of such a voltage.

During the past few years a type of X-ray exciter has been developed, notably in Germany and France, which gives what is approximately such a constant potential. Villard * appears to have been the first by use of his ionic valve tube (Fig. 283), to attempt this method, and later Greinacher † introduced a further method employing four valve tubes, as in Fig. 284. An apparatus of the constant potential type, employing four valve tubes, was used by Hull ‡ of the American G.E.C. as long ago as 1915 for experimental purposes.

The method is, in electrical practice, by no means a new one. As with many advances, for example, anti-corona apparatus, this has come to X-ray technology *viâ* the related wireless technology.

When the excitation of wireless radiations by valve apparatus first arose, it was customary to use high-tension batteries of a few hundred to 1,000 volts. Extension of the method soon rendered such batteries both expensive, inconvenient and cumbersome. The need therefore arose for small electrodynamic machines capable of giving voltages up to about 10,000 volts.

Whilst such machines offer no great difficulty in design and production, for the purpose for which they were intended, objectionable noises of audible frequency occurred, interfering with reception, due to the momentary interruption and sparking, as each commutator bar passed the collecting brushes.

It was soon found this interference could be largely eliminated by shunting a suitable condenser across the high-tension leads or brushes, which had the action of smoothing out this " commutator ripple."

The use of such condensers to accumulate high-tension energy and

* *Jour. de Phys.*, x, p. 28, 1901.
† *Verh. der. deut. phys. Ges.*, 16, p. 320, 1914.
‡ *Amer. Jour. of Rönt.*, p. 153, 1915; *Phys. Rev.* 7, p. 406, 1916.

This action is quite analogous to the condenser method of obtaining a continuous voltage or current.

A similar electrical circuit will constitute, in general, a non-oscillatory circuit since we have the aperiodic condition of negligible inductance, large capacity and large resistance. It can be shown that, for the acquirement of a final steady state we must have $\frac{R^2}{4L^2} > \frac{1}{LC}$ (p. 153, Vol. I.).

When L is not small however $\frac{1}{LC}$ will tend to $\frac{R^2}{4L^2}$ and the condition tend to oscillation unless C is also very large. In other words to maintain a steady value of oscillation C must be large, and as R is large, L must be very small.

It is obvious that between the source of energy and the condenser we must apply some means (such as a valve in the hydrostatic case) to prevent back surges of energy, if, in practice, the more convenient alternating source of high-tension energy is used to charge the condenser.

We may use for this purpose either a mechanical rectifier or a valve tube, preferably of the thermionic type.

As a mechanical rectifier the disc type is practically of no use, since

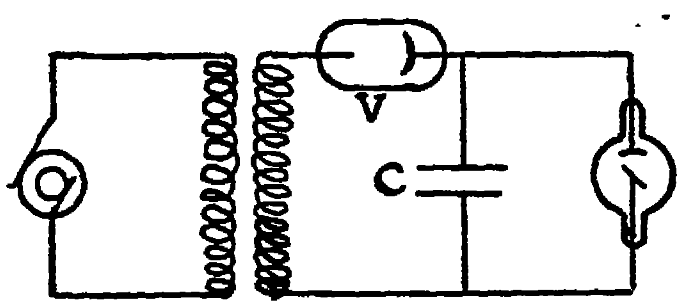



FIG. 283.—Villard Method.

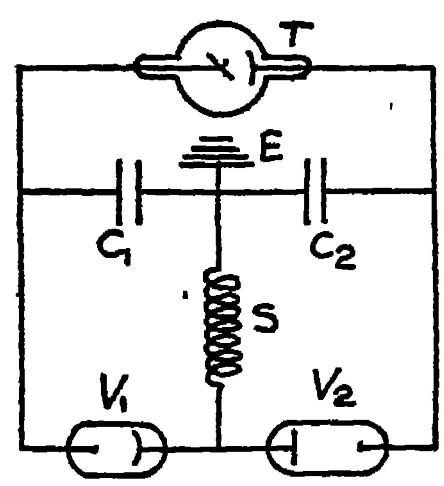



FIG. 284.—Greinacher Method.

the time of contact is so long that an arc occurs and is maintained so that the energy surges back during the period of the arc.

The point type of rectifier is alone possible, this giving a rapid rate of separation and tending to rapid quenching of the spark, a result which might however be quite equally reached by the well-designed toroid rectifier described on p. 320, where quenching would depend upon the low electrostatic flux distribution and the use of a small distance of separation promoting quenching.

With the simple diagrammatic arrangement shown of a valve tube V, condenser C and X-ray tube in Fig. 283, we are only utilising one half cycle, no current flowing during the other half cycle. Whilst the main loss of energy is then by iron losses of the transformer the sudden cessation is likely to cause undesired electrical oscillations.

If however we use two valve tubes (Fig. 284) in reverse connection then, during one half cycle, valve $V_1$ will allow the flow of energy into the

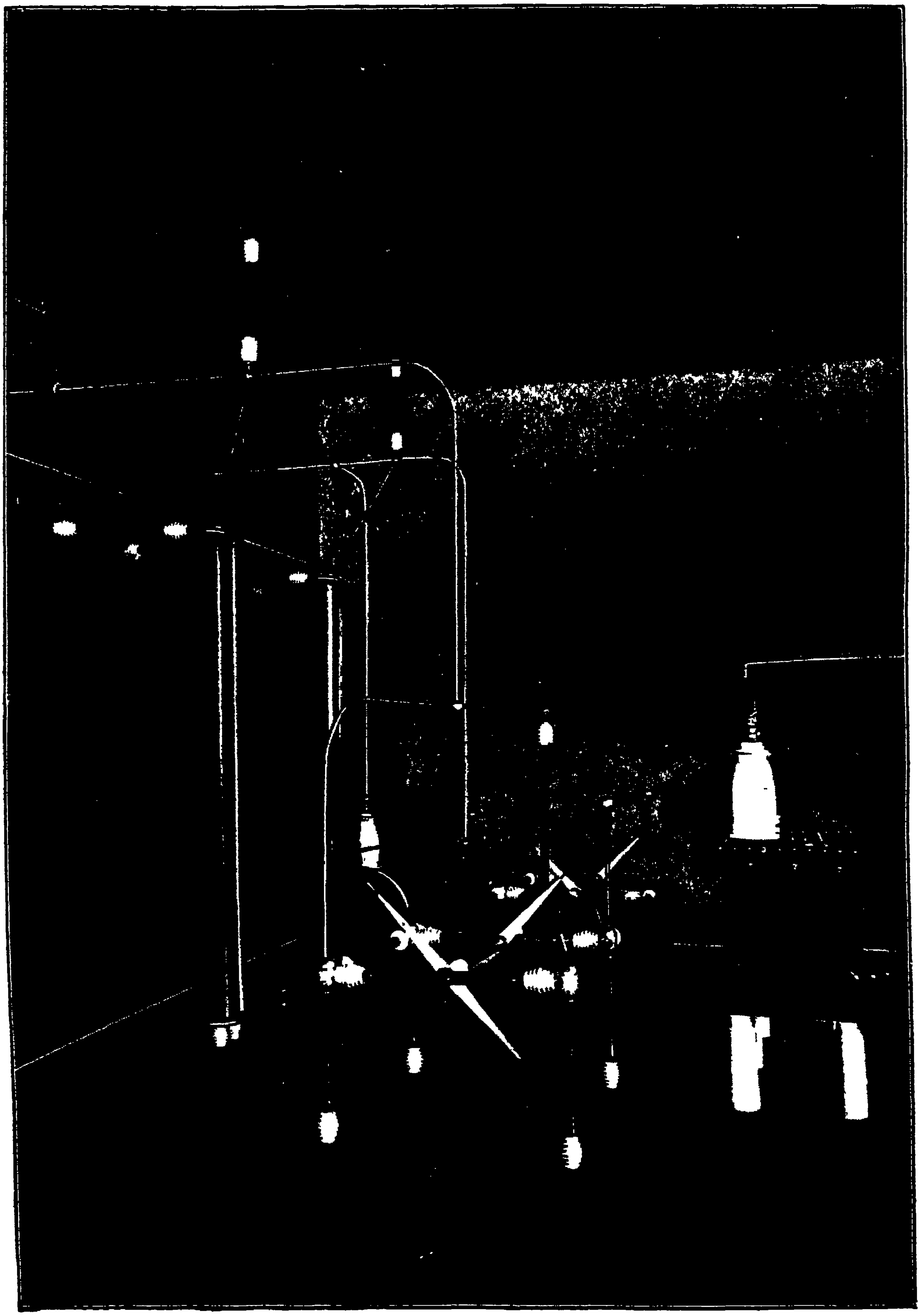


FIG. 285.—Neo-Intensive Apparatus (Viefa-Werke).

[To face p. 357.

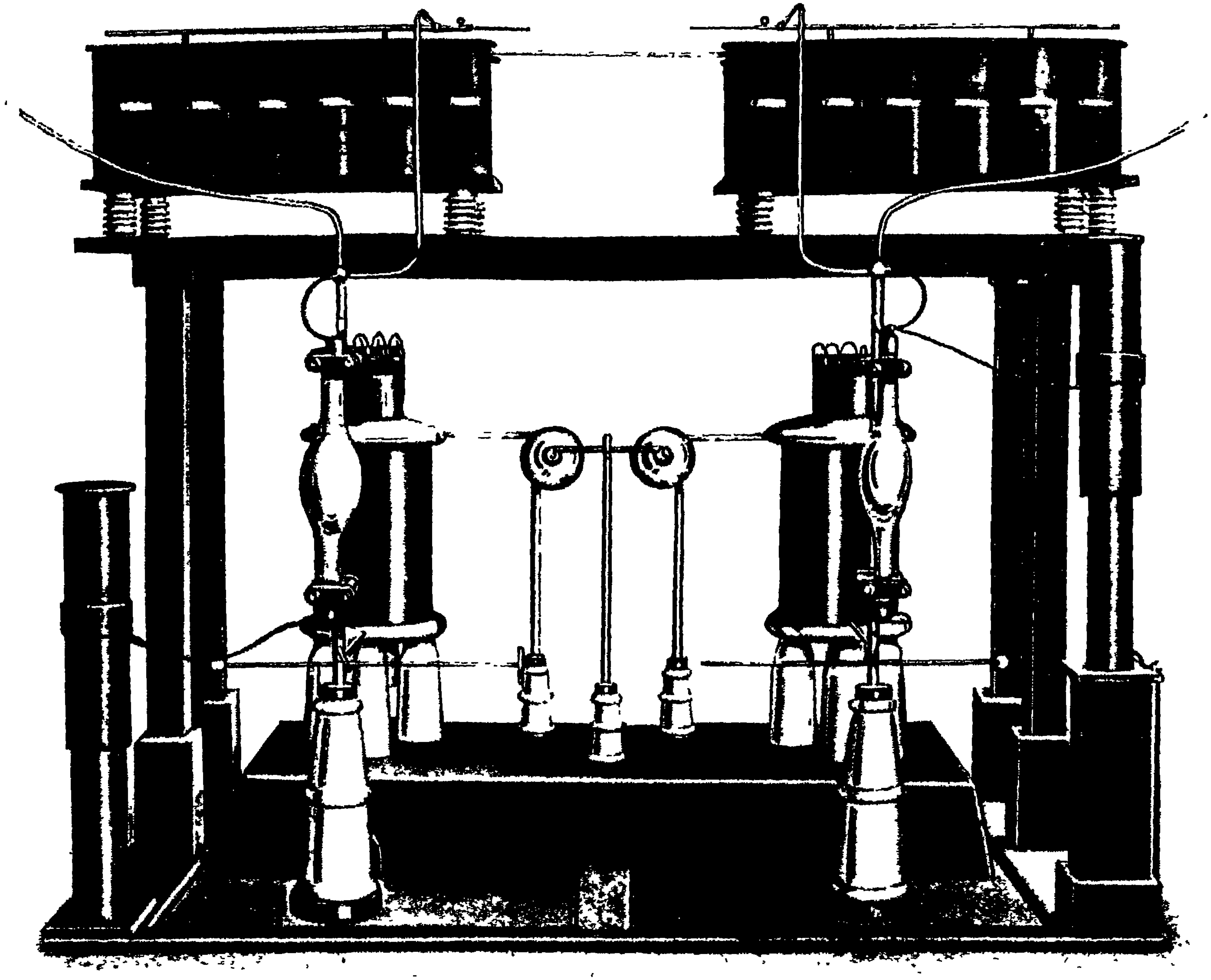


FIG. 287.—Constant Potential "Symmetry" Apparatus (Viefa-Werke and Reiniger, Gebbert & Schall).

[To face p. 357.

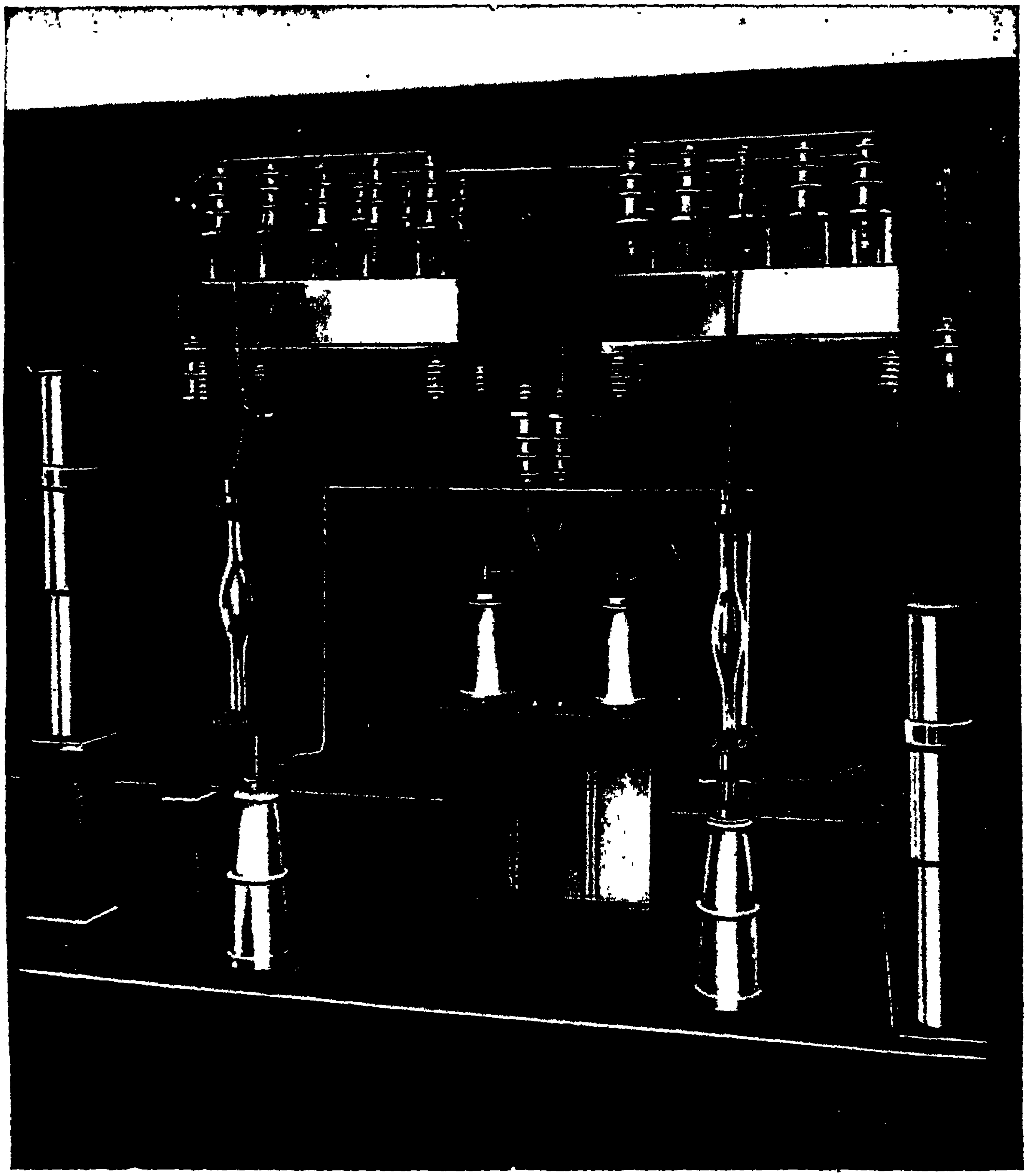


FIG. 288.—Dessauer Constant Potential Valve Apparatus (Viefa-Werke and Reiniger, Gebbert & Schall).

[To face p. 357.

apparatus in so far that, in the event of a valve breakdown, it can still be operated as an induction coil by means of the usual break.

A very complete form of apparatus is manufactured by Gaiffe, Gallot and Pilon of Paris for either 125 or 250 kv. the condenser arrangements for which are shown in Figs. 289 and 290, and are essentially as our fundamental connections of Fig. 284. It should be noted from these figures how resistances are inserted to cut down oscillations in the condenser circuits. Note should also be taken of the methods of obtaining a secondary voltage reading in Fig. 289 by measuring the leak current *viâ* a condenser V and in Fig. 290, by tappings upon the earthed ends of the two resistances where the electrostatic voltmeter

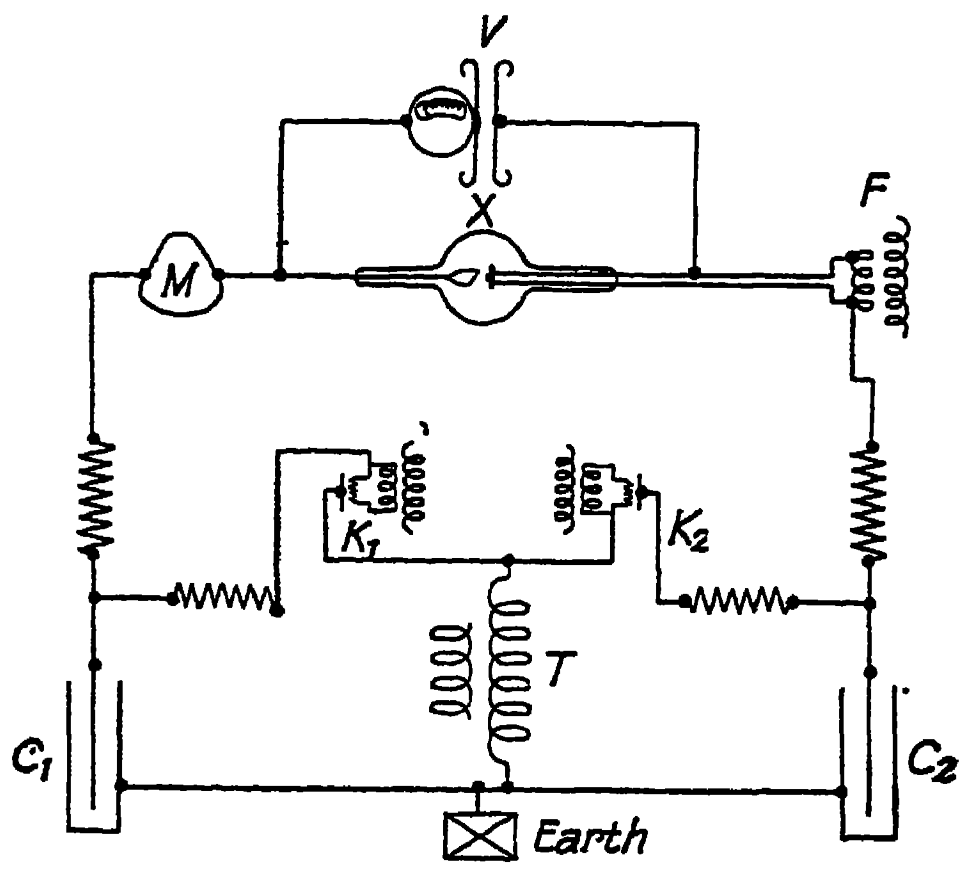



FIG. 289 (125 kv.).

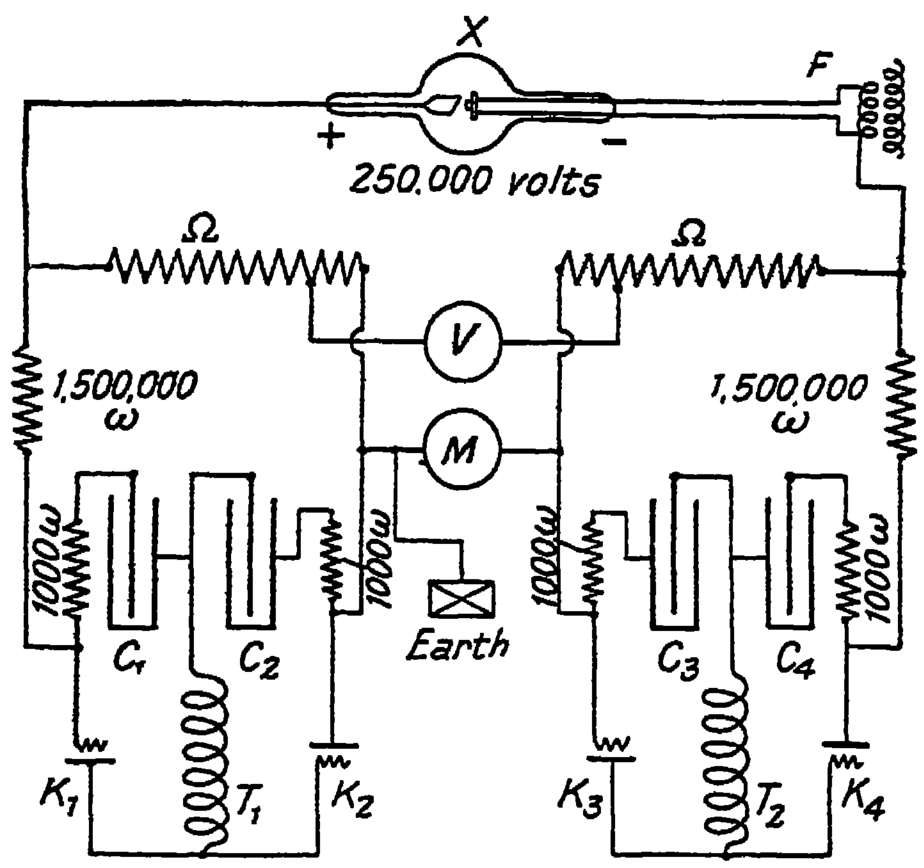



FIG. 290 (250 kv.).

$T_1$, $T_2$: two transformers, rated at 75,000 volts, connected in series, each charging two condensers to 62,000 volts, the margin allowed tending to prolong the duration of each discharge and so augment the constancy of the resultant current. $C_1$, $C_2$, $C_3$, $C_4$: condensers, approximate capacity 0·02 microfarads. $K_1$, $K_2$, $K_3$, $K_4$: electron valves. X: Coolidge tube. F: transformer for heating Coolidge filament. V: voltmeter reading to 250,000 volts in steps of 5,000; intensity of current measured reduced, for safety, by two resistances Ω of approximately 1,000 megohms each. M: milliamperemeter at earth potential.

V for 5 kv. is calibrated directly against the total secondary voltage. The voltage is regulated by a variable self-inductance in the primary circuit.

The appearance of this apparatus and the general layout may be better appreciated by Figs. 291 and 292, where the various components are indicated.

This apparatus having the milliamperemeter and voltmeter connected in the earthed mid-point of the transformer secondaries, these instruments can be actually touched without danger during operation.

Each transformer in the larger apparatus gives 75 kv. secondary voltage with a total of 250 kv. root mean square value, *i.e.*, 62·5 kw. volts per condenser. The secondary current is 10 milliamperes and the voltage variation is only 5 per cent. of the maximum value.

in conjunction with the oil-immersed tube dependent from a gantry as already described in Chapter VIII., Vol. II.

Whilst the apparatus is very beautifully constructed, it appears large in comparison with the German constant-potential apparatuses already described for which an equal output is claimed.

A constant potential apparatus for operation at 250 kv. has also been produced by Siemens and Halske under the title "Stabilvolt" apparatus.

This chiefly differs from the French apparatus by the employment of thermionic valve tubes, capable of operation at 225 kv., so that the valves are reduced from four in number to two.

Fig. 293 shows the connections of this apparatus.

One secondary terminal of the oil transformer is connected to the external coatings of two condensers, $C_1$ and $C_2$. From the other terminal two conductors are taken, each of which is connected to one of the hot-cathode tubes $V_1$ and $V_2$ and then to the inner coating of one of the condensers $C_1$ and $C_2$. The valve tubes are so connected that during one half period the current can only flow through one of the valve tubes to the condenser coatings, whilst during the other half period it flows through the other valve tube. They act as valves, permitting the current to flow in *one* direction only. Each valve tube is immersed in an oil-filled container, so that no sparks can pass along the glass body of the valve tubes.

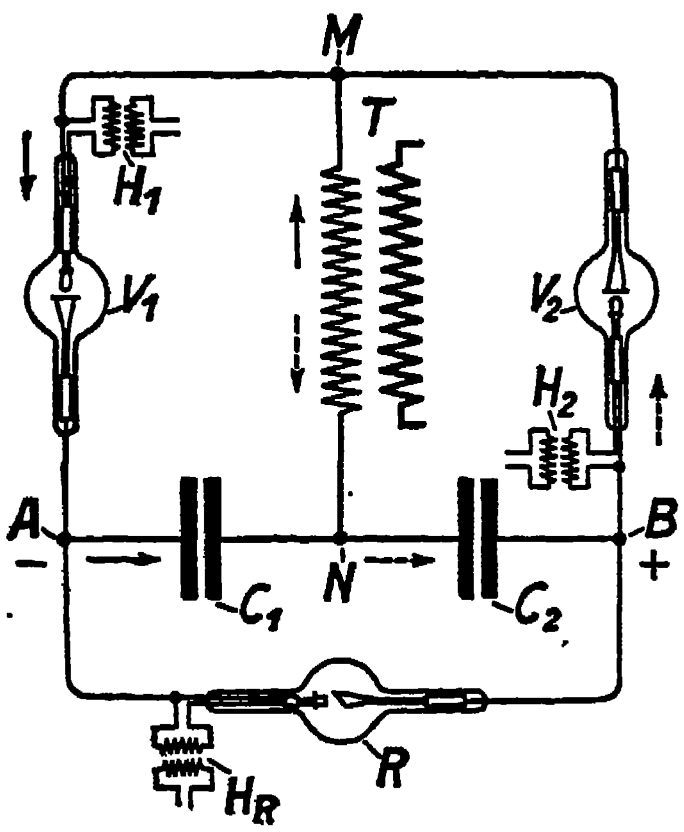



FIG. 293.—Connections of Stabilvolt apparatus.

The condensers are cylindrical in shape, and are made of material tested with about twice the working voltage. As the voltage at the condensers is practically a constant uni-directional one, they do not heat up and no puncture need be feared from this cause, as would be the case with alternating current.

The actual apparatus is shown in Fig. 294. The most prominent feature is the two large condensers. In the corner of the room is the oil transformer, which rests upon the unwound limb of the core and so facilitates cooling. To the left are the two rectifying tubes and above them the filament transformers. In the upper right-hand corner are two iron-core choking coils, which serve to prevent any superimposed high-frequency oscillations from passing to the X-ray tube, usually within a separate room.

The Stabilivolt apparatus gives tube voltages up to about 250 kv., at which figure the tube current can be raised to 10 milliamperes without causing a variation in the voltage of more than ± 5 per cent. If a greater variation is allowed, the tube current can be raised to 15 milliamperes.

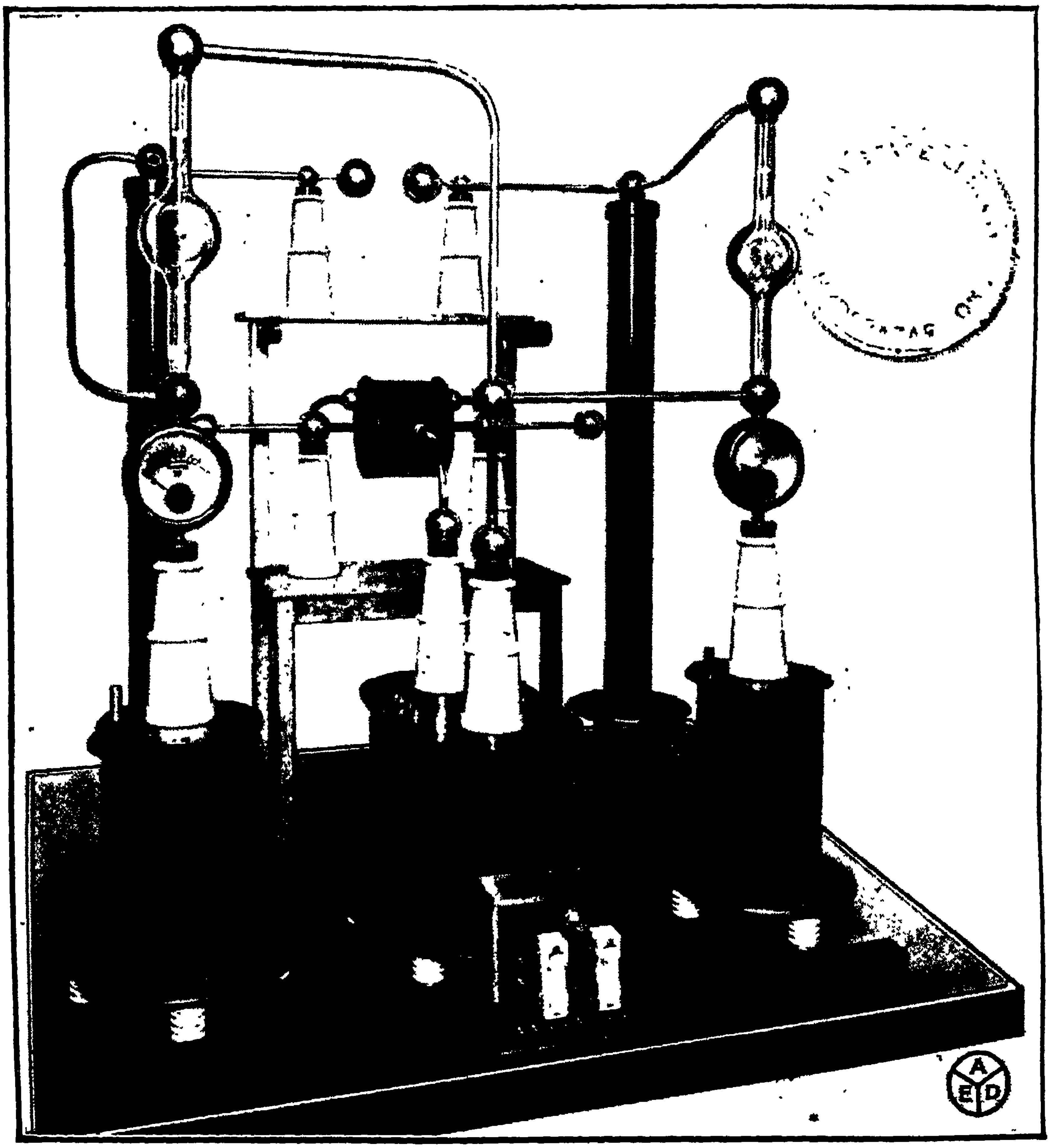



FIG. 298.—Constant Potential Apparatus (A. E. Dean).

*To face p.* 361.]

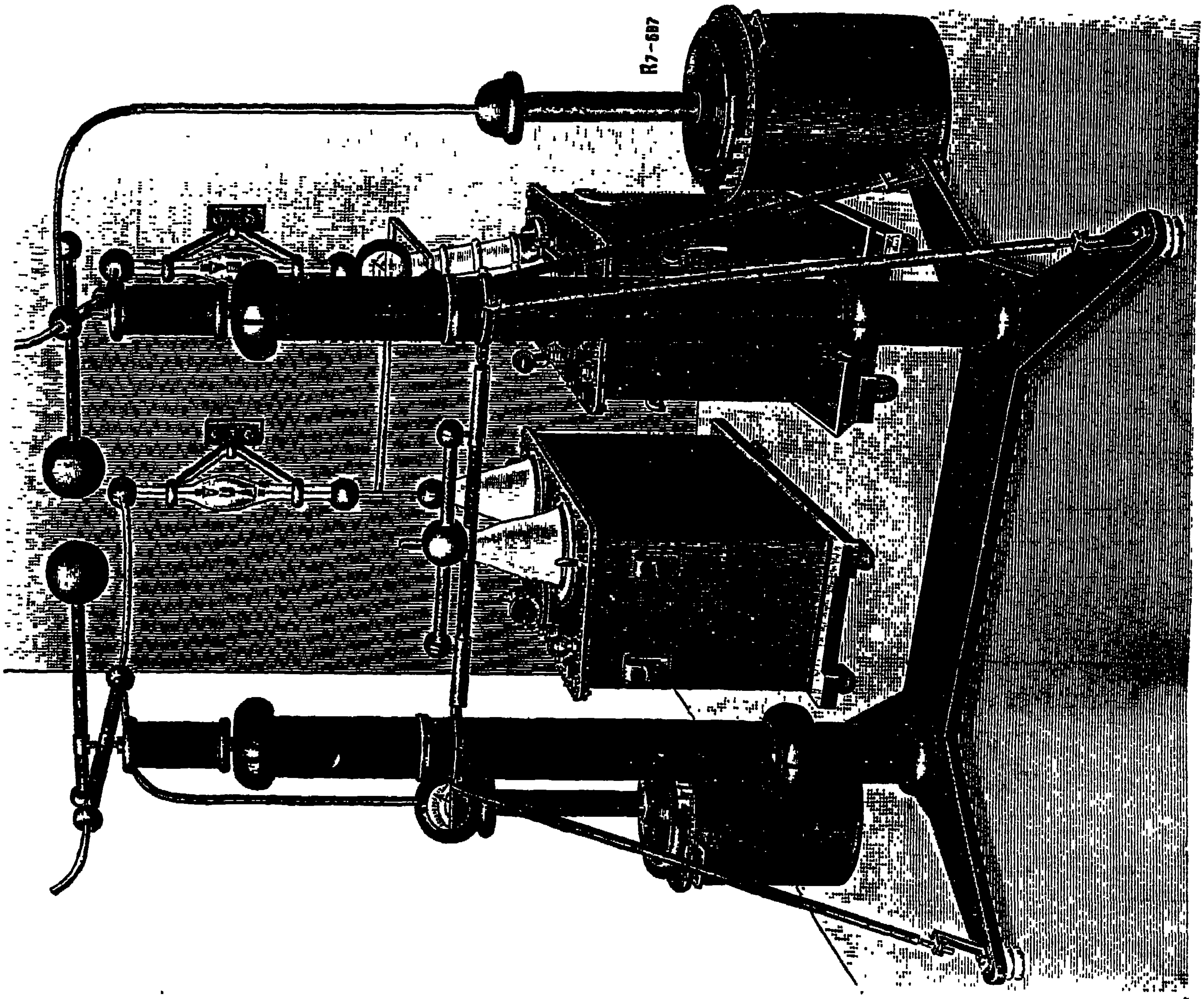


FIG. 296.—Constant Potential Apparatus (Koch & Sterzel).

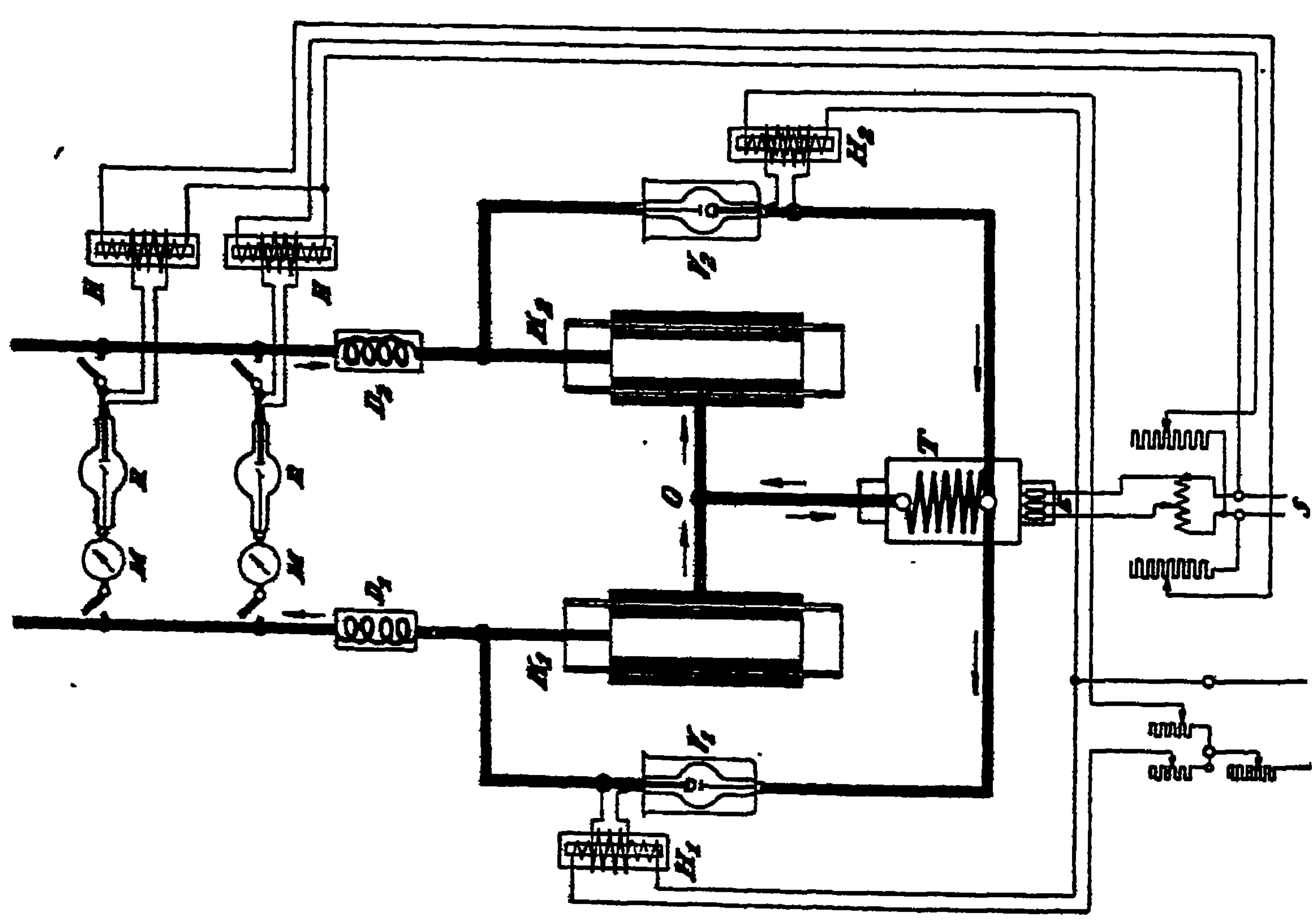


FIG. 295.—Connections of Koch & Sterzel. Constant Potential Apparatus.

a room lined with lead and earthed. The arrest of such oscillations by the metal, would generate heat due to the high-frequency currents and might be dangerous with an easily fusible metal as lead, a point which only practice can show.

(11) *Excitation by Means of High-Frequency Energy.*—From time to time the suggestion has been made to excite an X-ray tube with true high-frequency energy, *i.e.*, energy which oscillates with a frequency of the order of $10^6$ per second.

Many of the patents taken for such a method are obviously merely a method to allow the excitation of a low-powered X-ray tube, by means of a normal diathermy high-frequency apparatus, and therefore are of little importance.

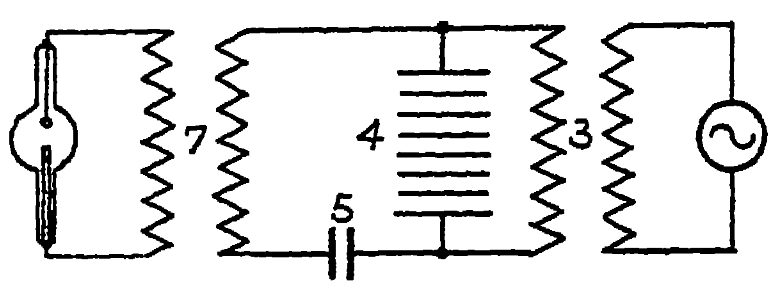


FIG. 299.

It is difficult to ascertain any specific advantages which are likely to be obtained by the use of high-frequency energy of the above order.

Whilst there is a definite advantage, with the use of alternating current of ten times the normal frequency, in that it allows a more efficient use of a suitable X-ray tube and greater energy output, this cannot be claimed for current of the order of $10^6$ frequency.

When large energy values of high-frequency current are employed, the practical difficulties with the comparatively low voltages used in wireless engineering (about 60 kv.) are enormous, owing to the tendency

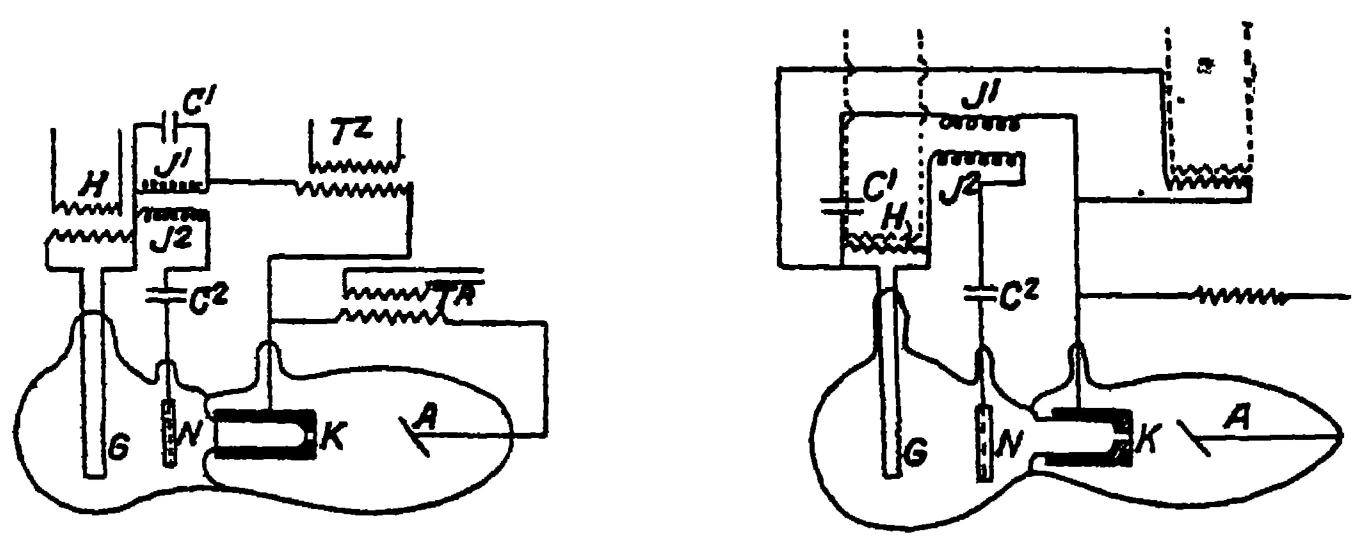


FIG. 300.—Lilienfeld High-frequency Method.

of such energy to pass *viâ* insulation and to give most erratic discharge effects. At voltages as used in X-ray technology (100 to 300 kv.) such disadvantages would be enormously increased. Special costly insulated transformers would be needed, and doubtless great modifications of the X-ray tube would be necessary.

Nevertheless, this method has been tried, but has never entered the region of practical radiology.

A hypothetical circuit for high-frequency excitation would be as Fig. 299, where energy is fed to an " excitation " circuit in which oscillations

A further high-frequency method of excitation is that of Loewe (Brit. Patent 149,013/1919), as shown in Fig. 302. In this the X-ray tube is itself used to generate high-frequency oscillations, since it is essentially a thermionic valve, such as used to excite oscillations for wireless telegraphic and telephonic purposes.

This tube has a thermionic filament cathode 11, heated by a battery 12 *vid* resistance 13. An auxiliary anode 15 and grid 14 are connected as shown to the cathode, and the oscillatory system 16, 17 and 18 acts inductively, on the one hand, on the regulating coil 22 of the grid 14 and, on the other hand, in the coil 23, which is connected with the main anode 24, or anticathode 25.

None of the above methods appear to have come into practical use. In addition to the insulation difficulties of all high-frequency energy, there is also the complication of these multiple electrode tubes, entailing a greater size and resulting increased surface and weight of X-radiation protection, with the attendant mechanical operative disadvantages. To overbalance these disadvantages there appears to be no obvious advantages of high-frequency excitation of X-radiation.

## THE RELATIVE EFFICIENCY OF VARIOUS FORMS OF X-RAY HIGH POTENTIAL GENERATORS

The literature of X-radiology will be found to give very many varying statements as to the relative efficiencies of various methods of exciting X-radiation.

Very few of these statements are based upon either a comprehensive technical or experimental knowledge and are merely an expression of opinion, rather than of fact. Most of the discussion centres upon the relative merits of induction coil and transformer.

In accepting such statements it is difficult to eliminate the personal factor.

When statements are made by some of the older radiologists, whose knowledge of electrical science is often small, allowance must be made for their natural conservatism against any change, introducing new methods with which they are not familiar. For the rational use of such apparatus they may or may not recognise their inability owing to lack of electrical knowledge, which they feel disinclined to acquire at an advanced age.

Similarly an induction coil manufacturer, who has gained a good reputation for the excellence of his induction coils, will naturally be adverse to the introduction of transformer apparatus, in the construction of which he has no greater knowledge and experience than other more recently established manufacturing companies.

The use of inaccurate methods of testing is again the cause of discrepancies. For example, the difference of ammeter readings when used

(2) transformer apparatus,
(3) induction coil apparatus,

the peak values all being equal and measured by some means as the X-ray spectrometer independent of the wave form, then we shall have curves as Fig. 303.

If our peak value is within the useful limit for the particular purpose

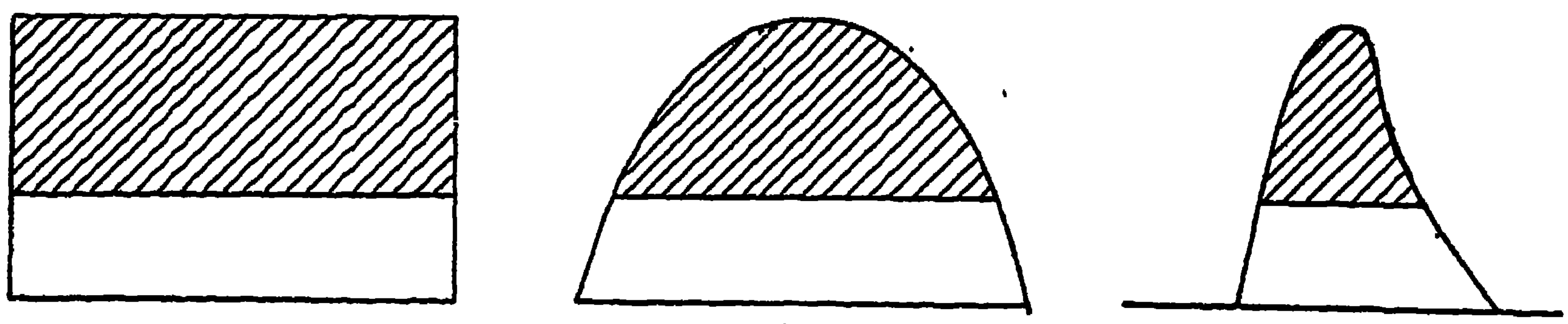



FIG. 303.—(*a*) Constant potential; (*b*) transformer; (*c*) induction coil.

of either radiography or radiotherapy then a certain portion of this total voltage is unuseful and has to be obviated by screening. Certainly in the case of the induction coil, this reduction can be represented by drawing a horizontal line, which represents the value above which the voltages give rise to useful radiation. In the case of the transformer, if the rectifier is so designed, only this useful radiation will be passed *viâ* the tube by correct adjustment of the rectifier.

This approximate method of eliminating the unuseful radiation in the case of constant potential is not so legitimate since the average electron speed tends closely to the maximum level value. A more obvious comparison would be as in Fig. 304.

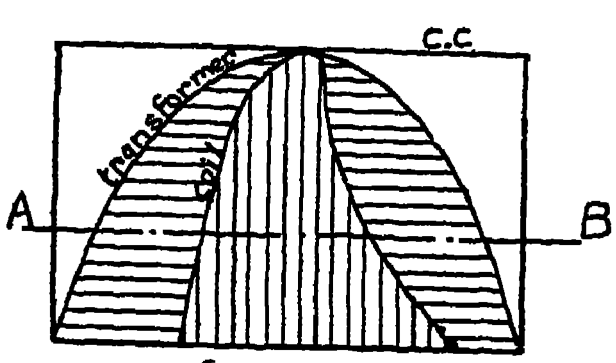



FIG. 304.

The intensity of the X-radiation will be the product of the average height of each curve and the product of time, the latter being considered as equal. It requires little consideration to see that the shaded areas which are the product of these values are in descending order;—

(1) Constant potential apparatus.
(2) Transformer apparatus.
(3) Induction coil apparatus.

Between each, if the voltage is correctly measured, there is a great difference.

The claim there is a great inherent and mysterious value in an induction coil type of apparatus therefore vanishes, if this is rationally considered. One may only say that if such a value is present we can equally obtain this by the use of some form of more convenient asymetrical alternating current generator, with which we have already dealt in Chapter V., Vol. I.

The former in either apparatus may be made of any desired degree by the insertion of suitable capacity, a procedure more easy with an approximately true sine curve of the transformer than with the irregular curve of the induction coil. A suitable value of capacity can nullify the whole current lag due to inductance and give voltage and current exactly in phase. The use of such a " leading " condenser in either apparatus may give rise to high-frequency oscillations. These can however be eliminated by the use of resistances, or " high-frequency devices."

Accepting the high peak of an induction coil as being largely true and not merely instrumental, it should be remembered that the current must, owing to self induction, lag behind this peak, and the current is so not, at the time of the peak voltage, actually passing *viâ* the tube. Such a peak voltage would however serve a useful purpose by breaking down the tube resistance and so rendering this conductive for the later current, which actually passes at a much lower voltage. Such an effect is not however a prerogative of the induction coil only, but may be obtained more reliably by asymmetrical transformer generators, or even better, in the normal transformer by causing the current to lag behind the normal sine curve peak, by an amount sufficient to allow for this prior breakdown by maximum voltage. This would however be only necessary with the gas tube and does not come into consideration with the electron tube.

Having now considered the theoretical aspects of this controversy we have now to see how this is borne out by experiment, which is the sole and final criterion. Much of the value of the available literature is rendered open to question since the experimenters have had a direct commercial interest in their results. A further source of prejudice is the use of apparatus loaned by X-ray companies for the purposes of such tests. It is readily conceivable that, if an X-ray company assists an experimenter by the loan of expensive apparatus which he cannot himself easily provide, there must necessarily be a certain favourable prejudice for this apparatus which there would not be if the apparatus was directly purchased.

Whilst not suggesting that an experimenter will give incorrect data owing to this reason, there must always be a subconscious tendency to read results more favourably, for example, the loan of a new transformer without charge would make the personal error always in favour of such an instrument as against a coil apparatus, which other manufacturers refused to lend and which had therefore to be purchased.

The instrumental methods of making comparisons of X-ray intensity of various generators are ;

(1) *By Spectrographic Methods.*—These are preferable as they show the relative intensities of components of different wavelengths.

(2) *By absorption methods,* in which the radiation is passed *viâ* various thicknesses of absorbing aluminium. The intensity, after absorption,

to give only 1 milliampere, as against 3 milliamperes with both the coil and transformer apparatuses.

(*b*) Since the coil gave 74 impulses per second whilst the transformer gave only 50 impulses per second. The values of the transformer should therefore be approximately $\frac{74}{50}$ times those actually shown.

Making these corrections the values should be approximately as shown by dotted lines, showing the great superiority of the constant voltage method over the transformer method and this in turn over the coil method for both gas and Coolidge tubes.

The results of Moore are summarised in descending order of efficiencies as follows ;—

(1) Constant voltage, with either gas or Coolidge tube.
(2) Transformer or coil with gas tube at high or medium voltage.
(3) Transformer with Coolidge tube.
(4) Induction coil with Coolidge tube.

The results of Moore are difficult to analyse since a large part of his paper is taken up in showing the superiority of the gas tube over the Coolidge tube. Whilst proving the superiority of constant potential apparatus (Transverter and three-phase rectifier) which is the same for either type of tube, he found little difference of coil and transformer for gas tubes, but a marked superiority of the transformer over the coil for Coolidge tubes, results which are identical with the (connected) curves of Dauvillier. The advantages he claims for constant potential are ;—

(1) Homogeneity of the X-ray beam as measured by ;—
  (*a*) Spectroscopic methods.
  (*b*) Absorption methods.
(2) Greater efficiency of the X-ray tube.
(3) The quantity of X-radiation is the simple product of current and time.
(4) Quality of radiation is directly proportional to voltage applied.
(5) Simplicity of dosage measurements in view of (3) and (4). The same would apply to exposures in radiography.

It should be stated that the intensity of radiation of an X-ray tube varies as the square of the potential. The intensity is really the product of voltage of excitation which determines the penetration and of the current which, assuming incorrectly, but approximately, the truth of some ratio of current and voltage similar to Ohm's Law, would give the current and voltage, from which it follows the intensity is proportional to the square of the voltage, a relation shown to hold good by various observers. We may also regard this from the Einstein-Planck hypothesis $\frac{1}{2}mv^2 = Ve = h\nu$, where, since the energy of X-radiation is proportional to the electron values of $\frac{1}{2}mv^2$ and since $v$ is proportional to V, then energy or intensity will vary as $v^2$, *i.e.*, as $V^2$.

A further paper upon the relative efficiencies, is that by Harlow and

79·5 and 77·5 kv. for Wimhurst, transformer and induction coil respectively.

Of the further measurements of relative efficiencies we may cite Owen and Bowes,* who state " the only definite conclusion that can be drawn is that, for large secondary outputs the Coolidge tube in coil discharge is not so efficient as the other combinations of X-ray tube and high-tension generators (coil and transformer) experimented with." The method of measuring voltage is a spark-gap method.

Of more value is a paper by Hull,† using the spectrometer method which shows the efficiencies in descending order to be (1) constant potential, (2) transformer (Fig. 310).

Behnken ‡ considers the relative efficiencies as shown in Fig. 311, but does not give data to support this view, treating the subject

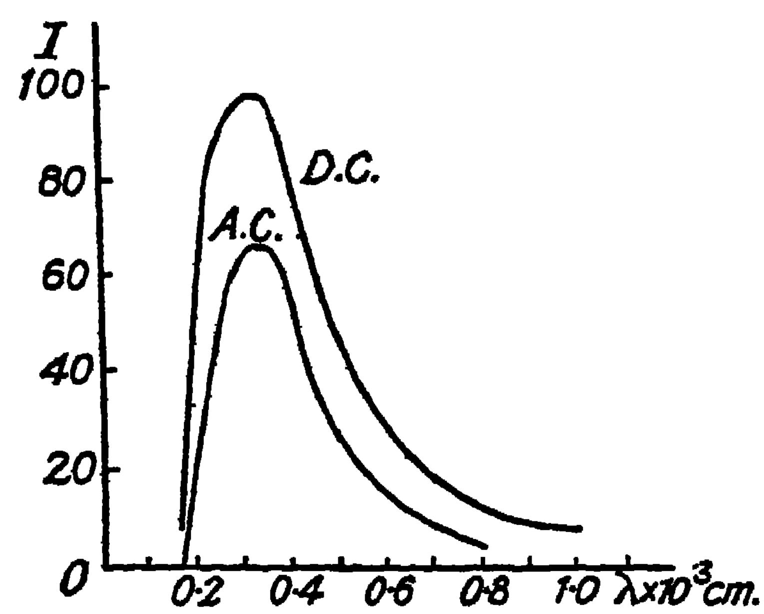



FIG. 310.

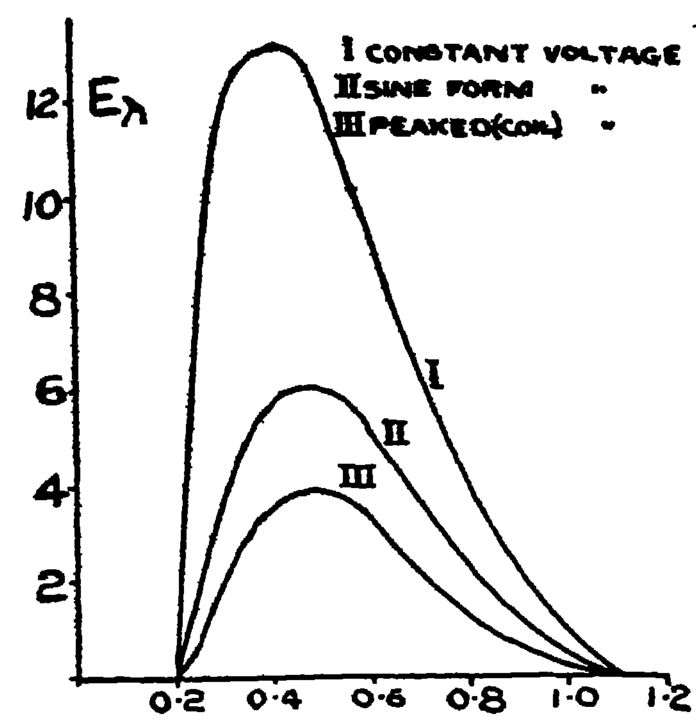



FIG. 311.

theoretically. He states the most suitable voltage is that which the ratio of $\frac{\text{maximum potential}}{\text{mean potential}}$ as unity, *i.e.*, constant current with a form factor of unity.

Duane § gives comparative curves of filtered radiation excited by continuous and rectified alternating current, methods which show a great superiority for the continuous current method.¶

Whilst the evidence is somewhat contradictory the most reliable investigations tend to show that, eliminating variations due to difference of X-ray tube used, the relative efficiencies are ;

(1) Constant potential ;
(2) Transformer ;
(3) Induction coil.

* E. A. Owen and P. K. Bowes, *Jour. Rönt. Soc.*, 19, p. 78, 1923.
† A. W. Hull, *Amer. Jour. Rönt.* (1915).
‡ H. Behnken, *Zeit. tech. Phy.*, 2, p. 153, 1924.
§ *Amer. Jour. Rönt.*, 9, p. 399, 1922.
¶ Glocker and Kaupp and also Nasledow and Kacura (see p. 371) find a relative intensity increase with constant potential over the intensities with coil and transformer of 1·5 to 1·6.

equal result is obtained more simply by increasing the single-phase frequency, as in the Radio-Silex apparatus. Both these methods are however more complicated than the use of a single-phase low-frequency transformer which is more simply converted, by use of a condenser battery, into a constant potential machine rendering the effects of frequency and phase negligible. Whilst the three-phase method has the advantage over the constant potential method, in that there is not such a great tendency to the simultaneous production of high-frequency surges, as in all transformer apparatus and particularly three-phase transformers, there must be a great tendency towards the production of harmonics (particularly the ninth harmonic) which tends to strain the insulation.

The Transverter method would appear to have advantages over both three-phase and higher frequency working. For low values of high potential energy it must necessarily be more expensive than the transformer and capacity combination. For large outputs (if suitable X-ray tubes can be evolved), when the space necessary for a large high-tension condenser battery would tend to prohibit the constant voltage method, the Transverter would be of extreme value, particularly in the possible X-ray installation of the future, where one large generator in a separate room will simultaneously supply all the X-ray tubes in various treatment rooms.

## EXERCISES ON CHAPTER VII

(1) Enumerate and briefly describe the various methods by which high-tension electrical energy, suitable for X-ray tube excitation, can be obtained.

(2) Describe the Transverter method of exciting high-tension electrical energy and discuss its advantages and possible applications.

(3) Discuss the influence machine for X-ray tube excitation.

(4) What are the practical advantages of the electron tube for small portable X-ray installations ?

(5) Apparatuses are manufactured abroad in which thermionic valve tubes replace the usual spark rectifiers of transformer apparatuses. Discuss their advantages and disadvantages.

(6) Compare the relative merits of exciting an X-ray tube (*a*) by three-phase energy, (*b*) by 500-cycle energy.

(7) Describe some type of " constant potential " apparatus and discuss the practical advantages and disadvantages.

(8) What precautions must be taken in comparing the relative advantages of various methods of exciting an X-ray tube ?

(9) Discuss the relative merits of (*a*) the induction coil method, (*b*) the transformer and rectifier method, and (*c*) the constant potential method of exciting X-radiation.

(10) Describe an apparatus utilising the Lilienfeld tube.

(11) Discuss the inherent defects of exciting an X-ray tube by high-frequency energy.

(12) What is meant by a " smoothing " condenser. Discuss its application to X-ray apparatus.

a most excellent apparatus may refuse, whereas a company making a very poor apparatus will readily accept, in order so to secure a valuable advertisement for an inferior apparatus. Similarly an inferior maker may offer an extended trial, or rather loan, before payment is requested. A financial committee, wishing to defer as long as possible the evil day of payment, may readily accept a poor apparatus on these terms and refuse a superior apparatus, for which immediate and inconvenient payment is demanded.

The intending purchaser should therefore refuse to be persuaded by the use of the name of the radiologists, or the better-known hospitals and, it is remarkable, that our best X-ray installations are to be found in the provinces.

The requirements of X-ray apparatus of the type we are considering are ;—

(1) As nearly complete X-ray protection as possible. It is not necessary to obtain certificates to this effect, as the medical man can sufficiently judge this himself, *i.e.*, if a totally enclosed tube box with three or more millimetres of lead is provided, there is no need to pay several guineas to know that this is provided when this may be more easily done by mere inspection.

(2) Easy movement of tube box and, if necessary, patient.

(3) Easy access to the patient on the part of the operator for palpation, etc.

(4) To be easily able to observe the patient and to converse with him, this being of great advantage with a nervous patient in a strange and darkened room. It should always be remembered that besides usually being ill, it is a strange and perhaps fearful experience for a patient to enter a darkened room, particularly with the older type of apparatus where the high-tension generator is not shut off from the operating room and sudden discharges may result. This condition is not always absolute, for example, some interposing shield is advisable where many tuberculosis patients are being continually screened in order to prevent the radiologist from breathing the same air as that of the patients, under the best conditions of darkness, etc., for him to be himself infected.

(5) Complete absence of any risk of direct electrical shock of patient, or operator, when working in the dark. The apparatus should be fed by an overhead aerial system and down leads to any apparatus pass down vertically.

To minimise shock, the leads, particularly to a table, should be encased in insulatory sleeves, or better, in such sleeves surrounded by an earthed conductor. Care should be taken in earthing apparatus (see p. 264, Vol. II.), and suitable earth terminals should be a built-in part of any apparatus. Failing such a method the down leads should be walled off by a wooden partition or better an earthed " expanded metal " shield of

been described. The high-tension energy may be fed to the tube from above with one lead either passing actually *viâ* an insulated tube in the box, or better *viâ* a tube outside the box.

This box must be fitted with a suitable diaphragm of at least 3 mm. of lead. Since radiation from the focus spot of the tube will proceed from different edges we shall get a "penumbra" in the regions A*a* and B*b*

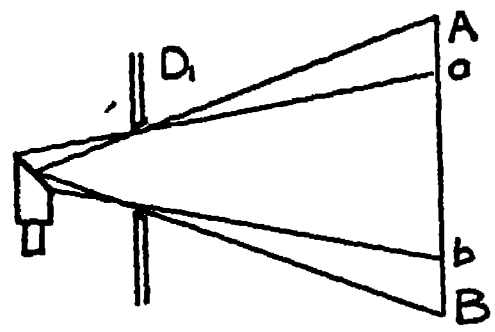



FIG. 312A.

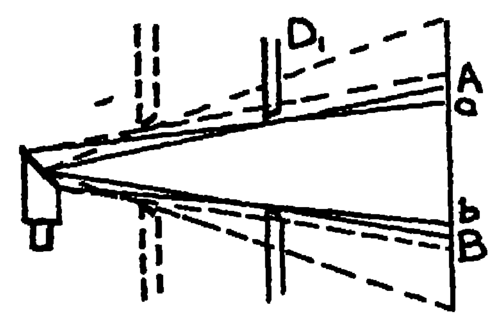



FIG. 312B.

(Figs. 312A and 317) which will serve to render definition in this region bad. Further the scattering volume *viâ* the human body will be increased and further loss of definition so result.

To prevent largely this penumbra, two diaphragms should be fitted at

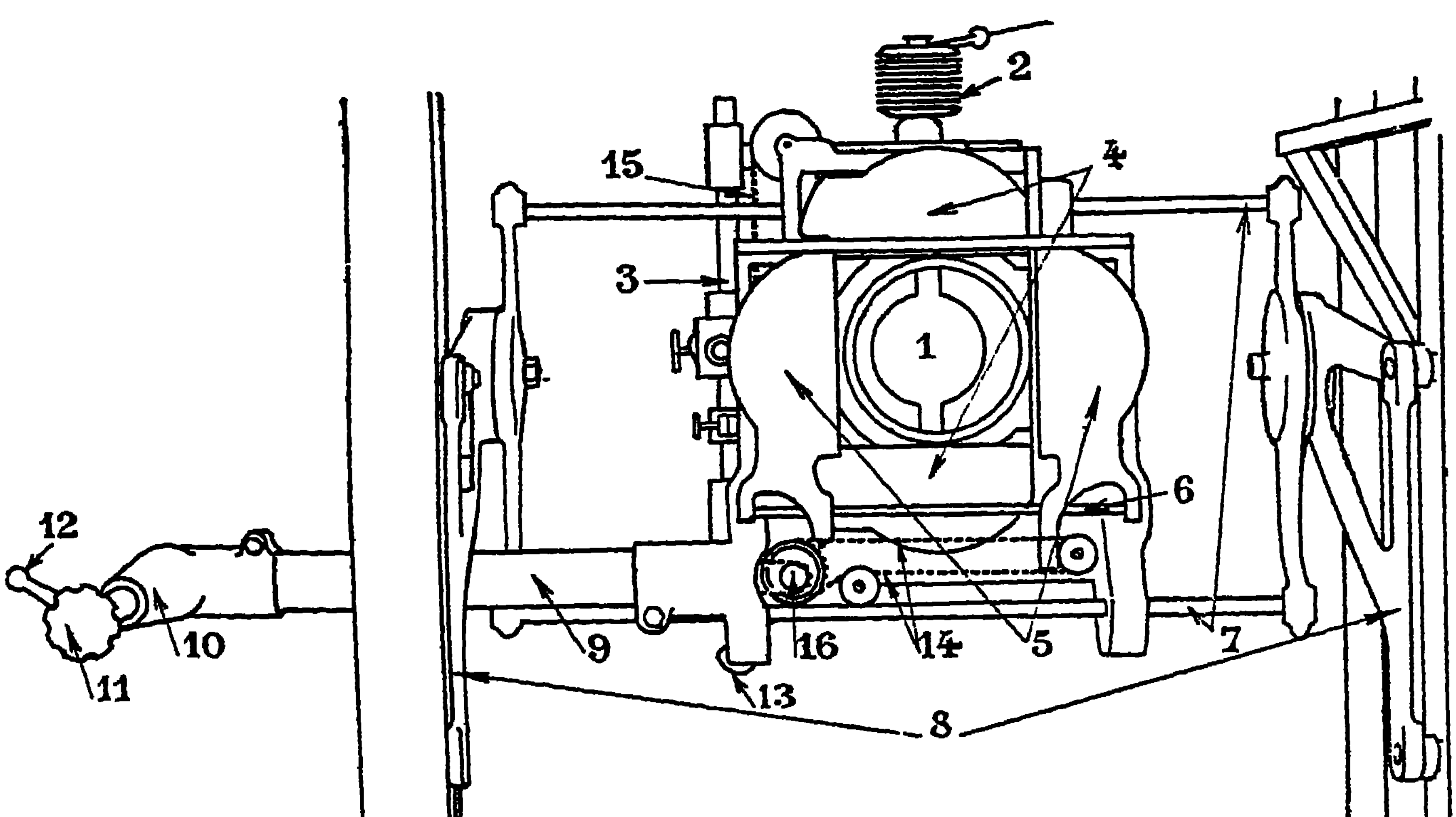



FIG. 313B.—Rectangular Diaphragm.

a distance of several inches apart, which will largely, but by no means entirely, obviate this penumbra (Fig. 312B). The diaphragm nearest the tube need only be a fixed diaphragm whilst that nearest the patient will be a shutter of four lead leaves, the movement of which, in pairs, is controlled either by levers or more conveniently, by a Bowden brake type of control.

A four-leaf diaphragm is shown in Figs. 313A and 313B. These leaves

The ray path between two flat diaphragms is best left open and not limited by a cylinder or box, as this will give rise to loss of definition owing to reflection refraction of those rays (Fig. 316) which are not strictly parallel to the direct path. With plane sheet diaphragms (Fig. 312B) these rays are able to escape as they are absorbed or further reflected away. (This remark applies also compression apparatus (*q.v.*).) A long cylinder however is preferable to two very closely situated or a single flat diaphragm as it does to a large extent cut down the obliquity of the rays. The diaphragm, particularly with electron tubes, should be fitted to take a filter of ·5 mm. aluminium, in order to cut down the unuseful soft

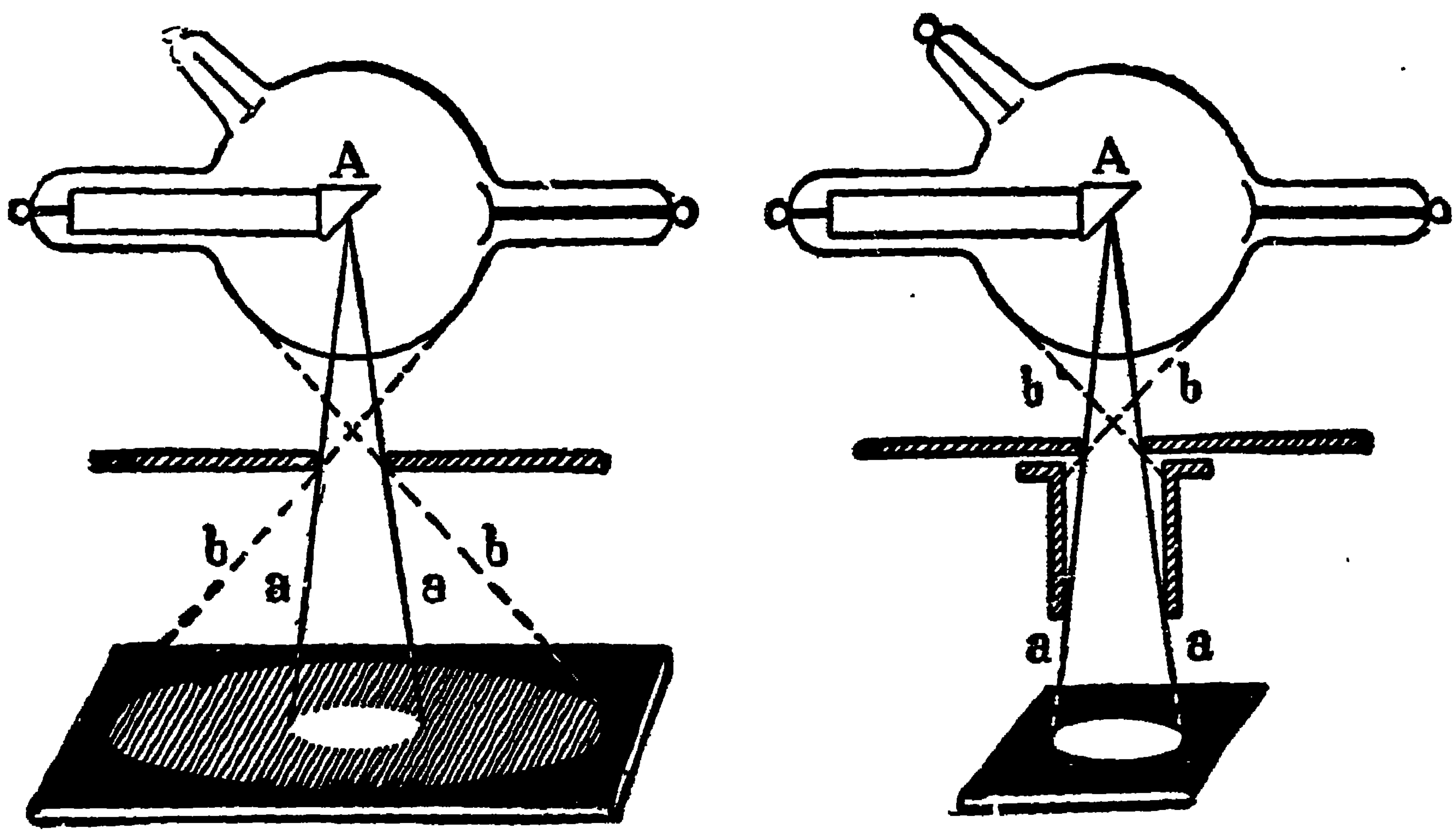



FIG. 317.

radiation which would be arrested by the patient's skin and perhaps cause burning, during a lengthy or repeated examination.

The screws fixing the diaphragm should not penetrate the lead protection or the tube box as it may cause point discharge and puncture of the tube if the tube box is of small volume.

The tube box, as regards its protection, has been dealt with (Chapter VIII., Vol. II.). We may capitulate that it should have a protective value of at least 3 mm. of lead, or equivalent lead rubber. It should be totally enclosed in the sense that there is no direct outlet for radiation except *viâ* the diaphragm apertures. If ventilation is necessary, as is usually the case, this should not be obtained by merely cutting out a window in the lower surface of the box, as is often done. In this case scattered radiation can pass from the box to be further scattered on the floor, etc., and then to impinge on the operator. Hence a ventilation window should be covered by a raised lead sheet, so that heated air can pass between box and sheet, but a baffle is so formed with respect to radiation. The leads to such a box are usually *viâ* the upper end in the

at the lower edge, when there is a great tendency for the heavy door to fall, as soon as the catch is released. Where the sizes of tubes used vary considerably a form of adjustable tube slide, as Fig. 319, is very convenient.

The tube box is usually mounted upon a frame or chassis, in turn mounted on ball-bearing rollers, moving along fixed supports of the screening stand or couch.

Lateral movement in the case of a screening stand, or transverse movement in the case of a couch, may in the more crude form of couch be obtained by merely pushing or pulling the tube-box frame. In the case of a couch, to permit this a long handle is provided, which is very objectionable since it protrudes from beneath the couch and is in the way of the operator's legs, and especially when the couch is used in the dark.

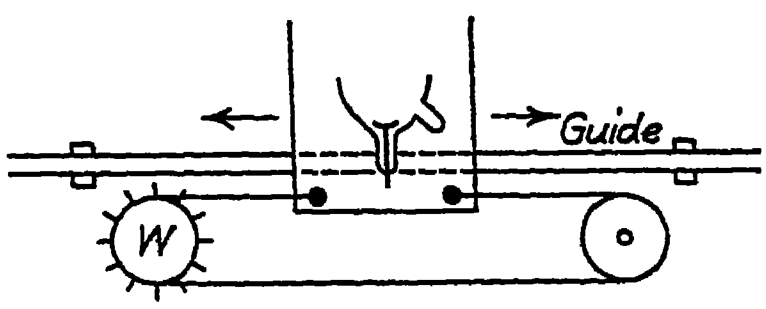



FIG. 320.—Mechanism to Move Tube Box.

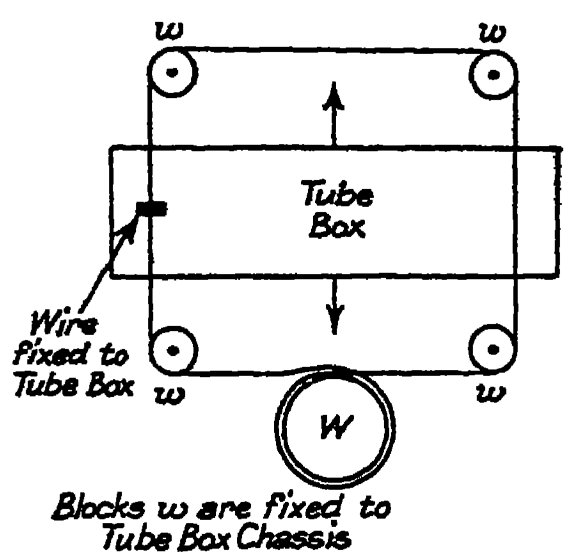



FIG. 321B.—Mechanism to Move Tube Box.

A much better method is to cause movement by means of a chain and sprocket wheel, as in Fig. 320, where rotation of the sprocket wheel W, by a suitable handle, causes the box to move to and fro along guides.

Especially for a couch, perhaps the best method is by a wire control (Figs. 321A and 321B), passing over a series of guide wheels *w* on the chassis and fixed to the tube box at F.

Rotation of a large and conveniently handled wheel W then causes to-and-fro movement of the tube box in the direction of the arrows.

The tube box with its diaphragm in a screening stand is given a vertical movement invariably by a counterweight mechanism, under the control of guides. These may be either a simple sliding guide, but better, a system of ball-bearing friction rollers. The counterweights of lead are usually bilateral to avoid jamming against the guides, but rarely, and less satisfactorily, consist of a single central counterweight moving behind the tube box.

The bilateral form is preferable as, in the event of a supporting wire

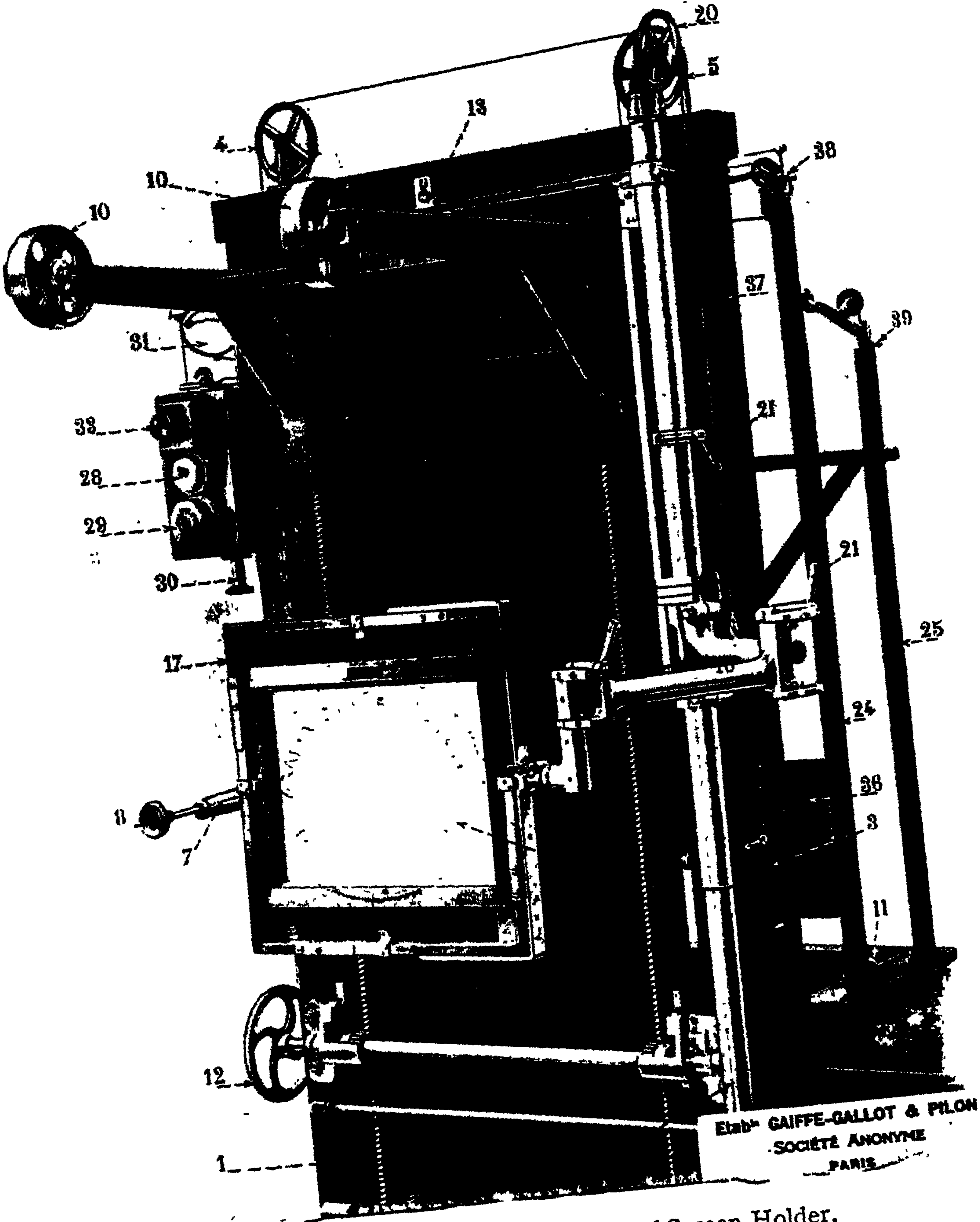



FIG. 322.—Unilateral Support of Screen Holder.

To face p. 385.]

raised as high as possible. Usually, the patient must stoop, which is often difficult for an infirm patient. This is a frequent cause of the patient's head knocking against the screen in the semi-dark of an X-ray room.

The mere suspension of the screen, by means of wires, as occurs in some foreign apparatus, is to be avoided since although it gives good screen motility it is obvious that owing to oscillation the screen will not always cover the tube box aperture and is therefore dangerous. Also it

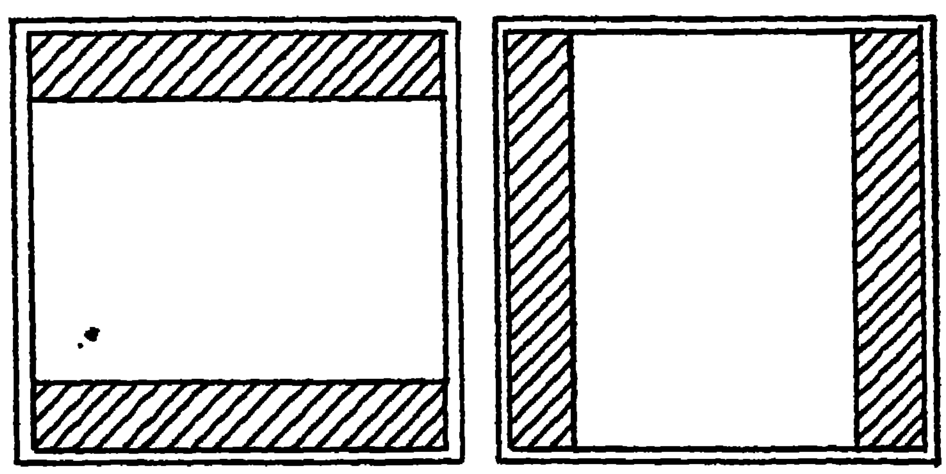


FIG. 325A.—Dangerous Screen Movement.

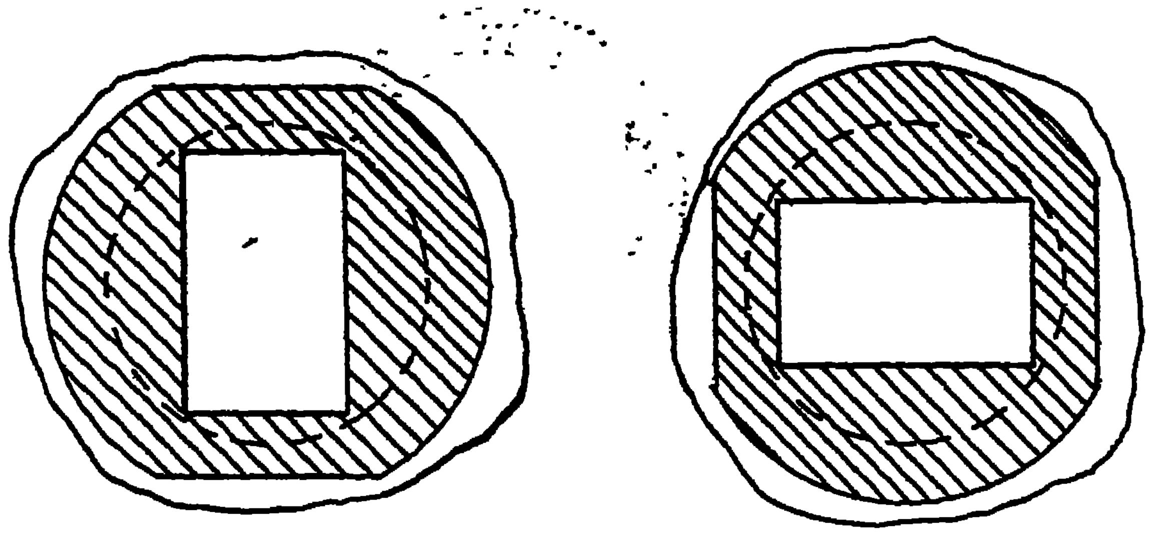


FIG. 325B.—Safe Screen Movement.

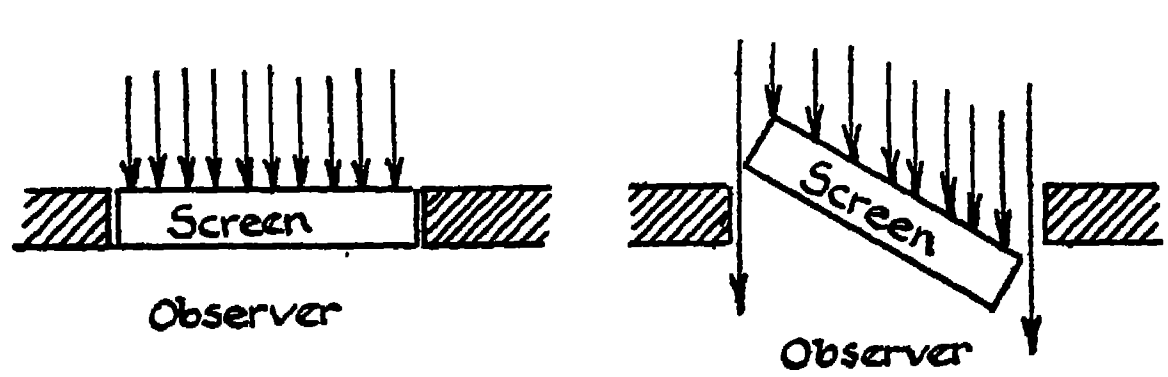



FIG. 326.—Danger of Screen Moving Obliquely.

is impossible to ensure complete absence of movement when the screen is replaced by a photographic plate.

The lateral movement is effected either directly, by mere pushing of the box and screen frame, or by means of a chain and sprocket gear (Fig. 320) which allows a finer control. All the bearings should be ball bearing.

The screen carrier is usually rectangular and is held in place by clips or bolts. It is better made in the form of a frame the front of which is hinged (Fig. 324), and has a distance of about 1 in. between front and

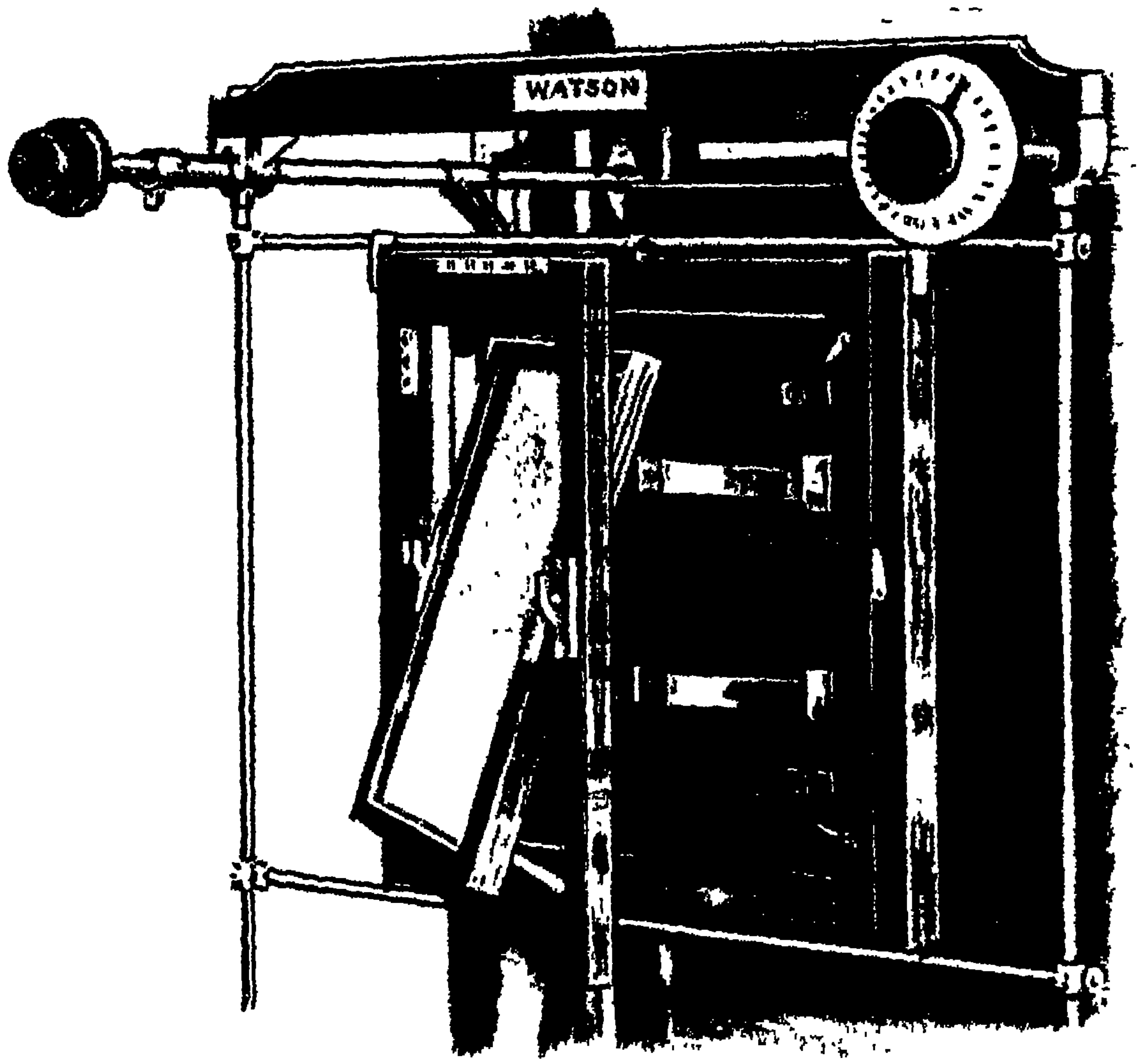



FIG. 324.—Screen Holder (Messrs. Watsons).

[To face p. 387.

The uprights, upon which the tube box and screen slide, may be directly screwed to the floor but are better fixed to a heavy casting having a fixed insulation mat. This better allows the whole apparatus to be earthed.

Occasionally a seat for a patient is provided but rarely used, as this necessitates the radiologist being in an uncomfortable low position.

More rarely a screening stand is fitted with a winch which allows the patient to be raised upon the platform. This type of apparatus is usually made to suit the requirements of individual radiologists and was long used by Albert Schönberg. It is of doubtful necessity as the result is merely that of shifting the tube box itself which can be contrived by less complicated and more convenient mechanisms. Modern apparatus of this type raises the patient by hydraulic means as in the modern operating table.

A refinement is the provision of a turn table, to allow the patient to be rotated about its vertical axis (Figs. 327 and 328). A still further refinement is to have a seat which can be both rotated or raised by means of worm gearings, but this is practically unnecessary. It is more practicable to have an ordinary music stool capable of being raised. This is normally not used but can be quickly placed in position to allow a weakly patient to sit during examination when the radiologist has a preference for vertical examinations. Handles at the side for a patient to grip are very useful, expecially for children.

The protection of the screen carrier should extend upwards and downwards. As the extreme vertical movements are never required, a vertical extension upwards of 6 in. and below of 12 to 15 in. is sufficient, if the diaphragm is correctly adjusted, this protective distance being merely to prevent radiation by scattering, within the patient's body. The distance of tube focus to the screen should be at least 30 in. to give no great distortion due to obliquity of the rays.

Between patient and tube box a wooden or paxolin " compression board " is placed to prevent direct contact of the patient and tube box which, if the tube box is unearthed, would cause a severe static shock. This " compression board " has no use as such, but may be used to compel the patient to stand close to the screen by bringing it forward. This board should be screened before use to make certain metallic particles are not incorporated in it, giving rise to shadows.

Suitable handles should be provided to allow the patient to support himself, if necessary.

Recently it has been recommended that lead-rubber side curtains should be hung at each side of the patient.

This is a non-practicable recommendation, devised in the physical laboratory instead of in practical radiology. Most makers arrange for these curtains to be removed.

viewing by a mirror as shown diagrammatically by M in Fig. 330, have never been more generally adopted, which would give greater protection and better luminosity, providing that total absorption behind the reflector is provided, the obtainance of which is a matter of experiment.

An American example of such an indirect viewing arrangement is shown in Fig. 201, Vol. II. A further example is the Chaoul duodenal apparatus (*q.v.*).

The author when dealing with children uses a "cryptoscope" arrangement (*q.v.*) fitted to the normal protected screen. This allows a child to be screened whilst the child is in the light, a very considerable desideratum with refractory and nervous children.

The illumination is practically that when normally viewed in the dark and it is surprising this simple device is not more generally used.

In the author's opinion the following are the chief points in the selection of a screening stand ;—

(1) A sufficiently large tube box, preferably of cylindrical, rather than square form, from which it is impossible for radiation to be emitted except *viâ* the diaphragm.

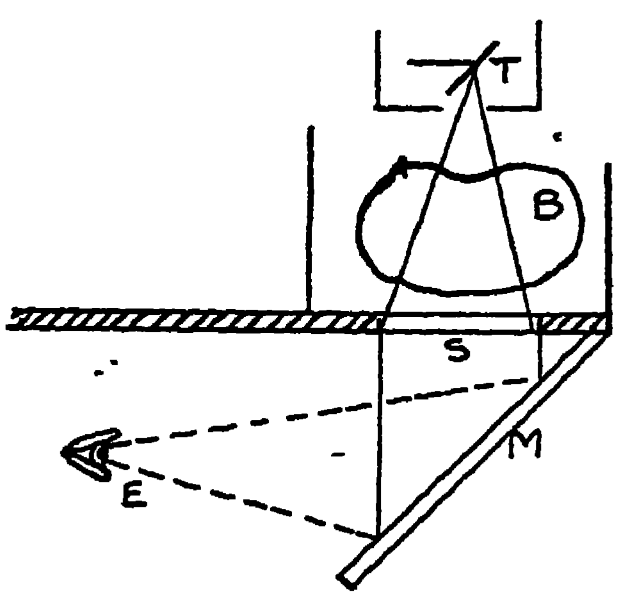



FIG. 330.—Indirect Viewing.

(2) A protective value of at least 3 mm. of lead or equivalent lead rubber, so applied that all seams and joints overlap.

(3) A self-focussing and self-centring tube slide.

(4) Tube box and fluorescent screen to move synchronously, with interconnection on one side only, the patient entering behind the screen on the other side.

(5) A tube-target-to-fluorescent-screen distance of at least 30 in. The diaphragms to be so adjusted that the illuminated area upon the protected screen is within the screen borders, when box and screen are at their maximum distance apart.

(6) Counterweights to have double wire connections and two counterweights to be present.

(7) Suitable buffers to prevent jarring in the case of sudden rise or fall of the tube box.

(8) The distant high-tension lead to pass in an insulated tube outside and behind the box.

(9) No lateral uprights to be present which can cause scattered radiation to fall upon the operator.

(10) A lead-glass protection of at least 2 mm. lead equivalent.

(11) Preferably all-metal construction with provision of an earthing terminal. All bearings to have ball races.

(12) Simplicity of diaphragm controls and controls for lateral and vertical movements.

*i.e.*, if hand wheels are used having a common centre, they must differ greatly in radius. Bowden brake controls should be mounted so that the distance between the controls allows them to be easily distinguished, levers should be of different lengths, etc. This is a most important point in practice. In the showroom, in full light and without gloves, controls will always work well, in the darkened X-ray room, with cumbersome gloves, closely situated and indistinguishable controls will not work well.

The tube box is fitted to two sets of ball-bearing rollers to give the desired longitudinal and lateral movements.

The lengthwise movement is usually obtained by mere displacement and rarely is a chain-driven movement arranged, as this is usually unnecessary.

The transverse movement is obtained either by merely pushing a transversely situated rod or more easily by means of a rotating handle (Fig. 332).

The circularly moving handle is preferable, as it does not so greatly get into the way of the operator's legs in the dark. Where the protruding handle method is used the disadvantage of this may be overcome by hinging this handle (Fig. 333) at every 2 in., so that, when the tube box is farthest away from the operator all the handle is rigid owing to the direction of the hinges and, when the tube box is nearest the operator, the hinges cause the handle to fall down the side of the table, instead of more inconveniently protruding.

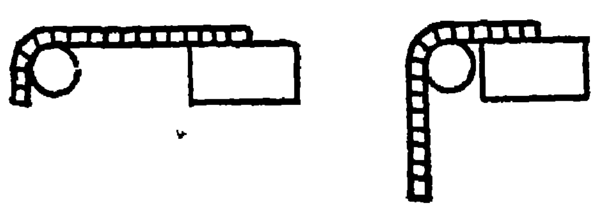


FIG. 333.

Less occasionally this transverse movement is produced by means of a foot stirrup. This, whilst more inconvenient to operate at first, after experience leaves the hands entirely free.

The tube box is mounted upon or hung by long steel rods, which should be sufficiently stout to prevent sagging when the box is at the centre position. The occasional use of rests to support the rods in the centre should be unnecessary and is unsightly.

Rarely are end springs provided to prevent jarring due to too rapid movement of the box along these rails.

Where it is desired to do much colon investigation, the table may be conveniently arranged, by means of ratchets, to allow either end to be raised, or lowered (Fig. 336). Except for such work this adjustment is of little use, adds to the expense and gives more mechanism to keep clean.

A simple lock can be provided upon either form of box movement in both directions. To give a stereoscopic shift of 6 cm., a suitable calibrated slide is provided.

The leads to the tube box are preferably taken to a common end of the table and the down leads protected by insulating tubes, preferably surrounded by earthed metallic shields (Fig. 195, Vol. II.). Where such

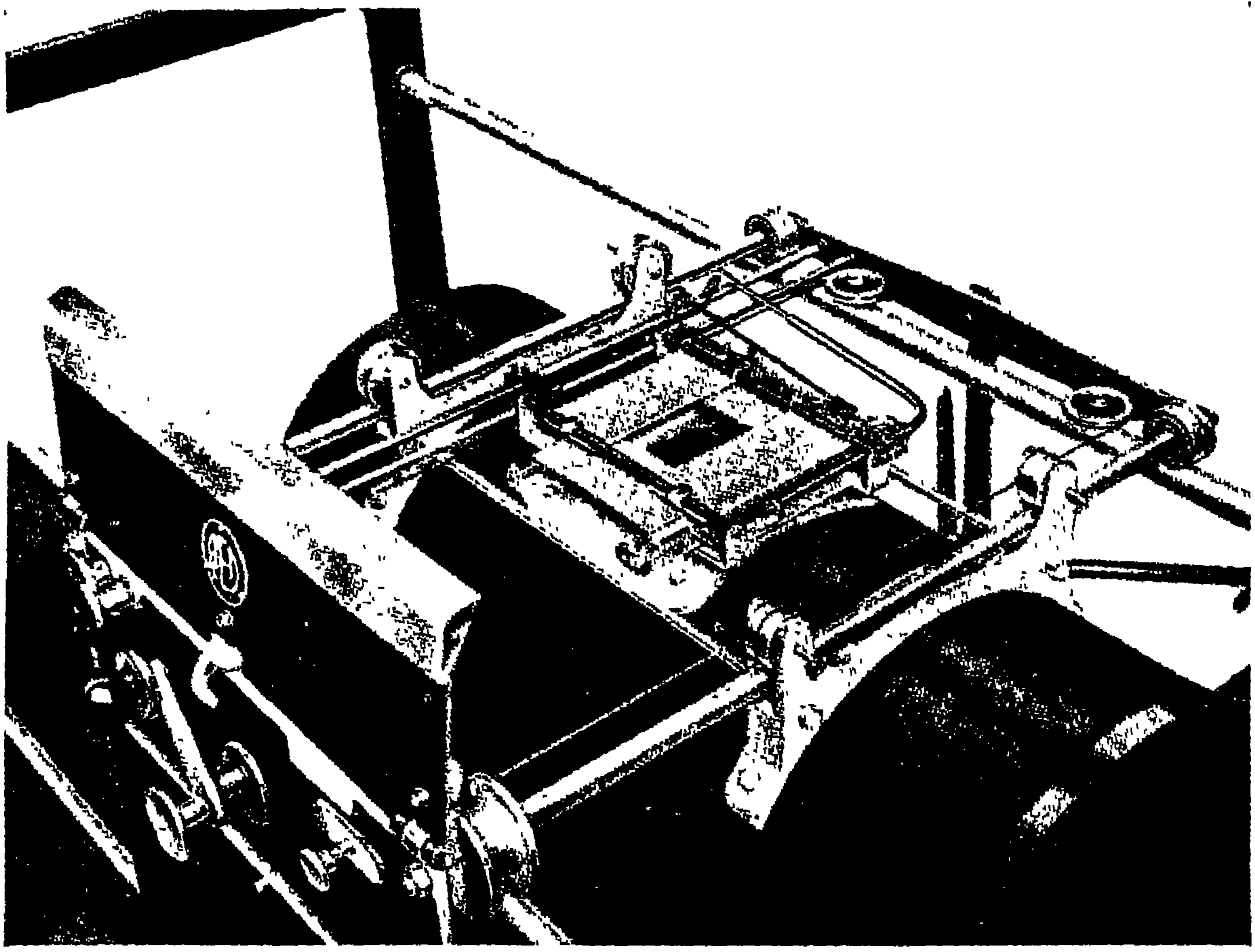


FIG. 332.—Undercouch Tube Chassis (A. E. Dean).

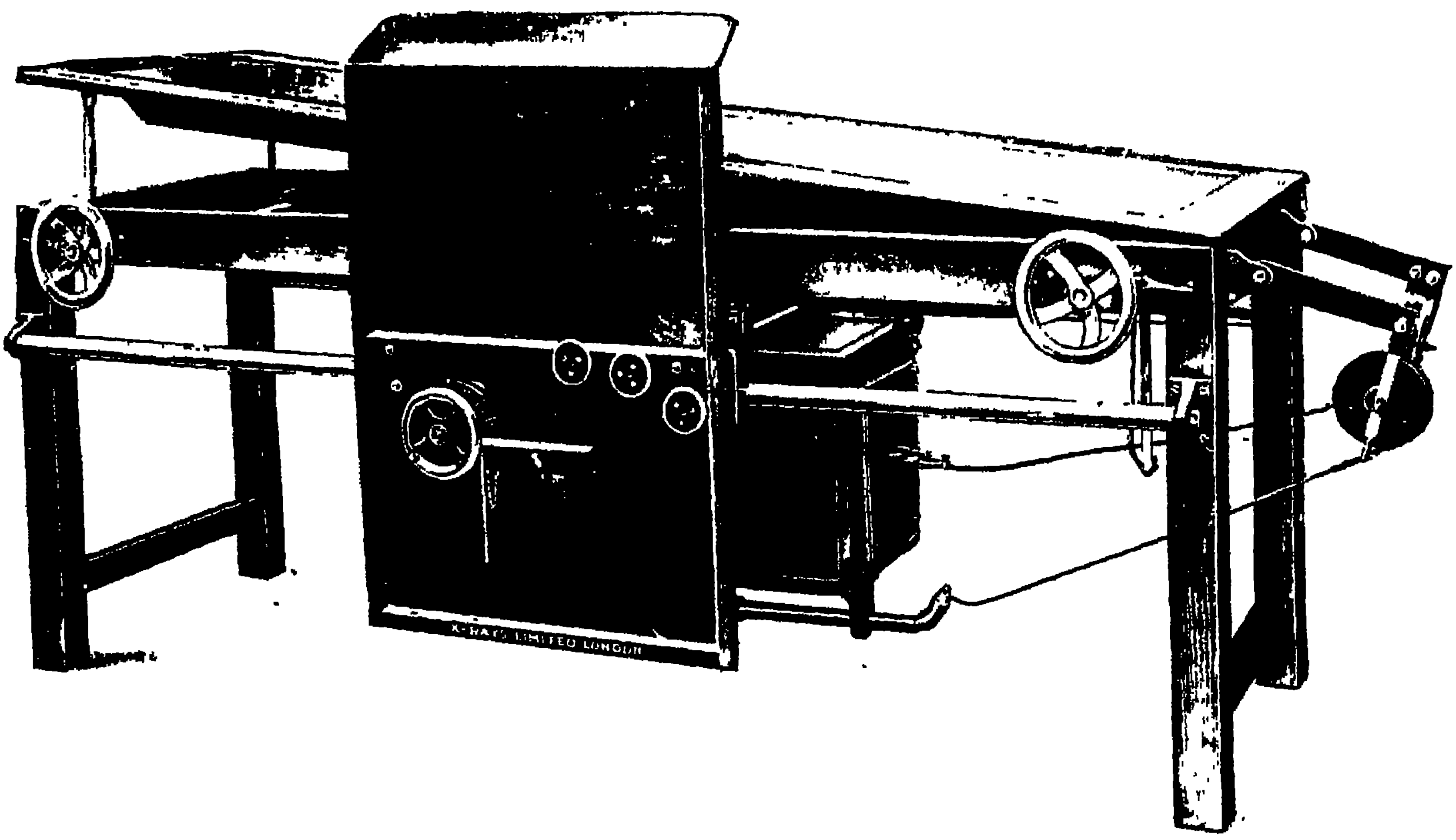



FIG. 336.—Table to protect against radiation scattered from patient's body (Messrs. X-Rays, Ltd.).

rigid upright as in Fig. 340, where the various mechanisms to raise, tilt rotate and to move the tube transversely are shown.

Connections to the tube are made directly downwards by connectors from the aerials above, or directly upwards *viâ* the floor.

Fig. 341 illustrates a convenient method of fixing the screen on a swivel movement, so that this may be, at will, swung out of the way.

## COMBINED COUCH AND SCREENING STANDS

Where the space devoted to radiography is restricted and very much work is not carried out, it is often advantageous to have an apparatus that, upon need, can be used both as a couch, or as a screening stand.

Where space is available such an apparatus, which is necessarily restricted in its application in some manner (*i.e.*, is very good as a couch and very inconvenient as a screening stand, or *vice versâ*), is inadvisable. There is little saving in cost compared to a simple couch and a simple

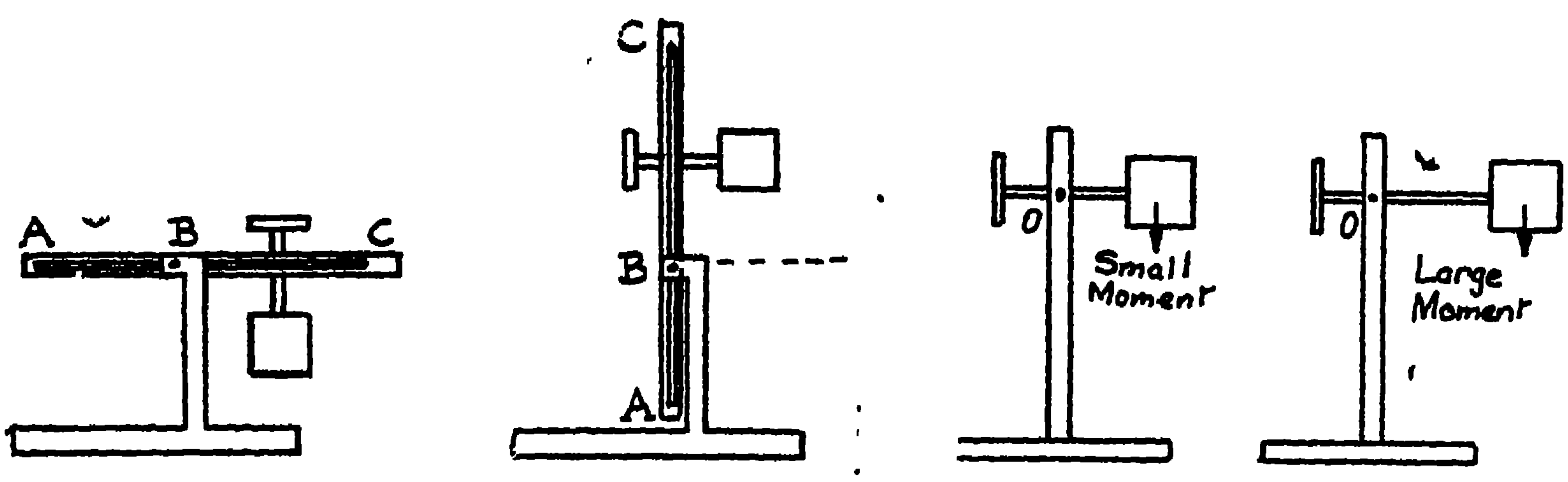



FIG. 342 —(*a*) Movement restricted lengthwise; (*b*) movement restricted downwards; (*c*) moment about O reduced, tube box and screen distance small; (*d*) large moment about O.

screening stand since, to allow the requisite movements, the mechanism is necessarily more complicated. In some cases, such an apparatus actually costs more than two separate apparatuses. In one case such an apparatus costs several hundred pounds.

The defects of such an apparatus will usually be found to be;

(1) It is impossible to obtain a complete range of movement of the tube box and screen carrier in the long axis, when used as a couch, owing to the supporting framework (Fig. 342, *a*).

(2) It is impossible to obtain a full movement towards the ground when used as a screening stand. This is particularly objectionable with children (Fig. 342, *b*).

(3) It is necessary to counterweight the heavy tube box. The heavy box exerts (Fig. 342, *d*) a considerable mechanical moment about the screen plane. It is therefore necessary to place the box (Fig. 342, *c*) as closely as possible to the screen plane, which reduces the target-to-patient distance and causes distortion.

(7) Down leads to be encased in insulating material to a height of 6 ft. above ground. The insulating tubes to be further encased in earthed metallic cylinders. Such down leads to be at least 12 in., from the table edge.

(8) A distance between tube focus and couch top of at least 18 in., and preferably greater.

(9) The traverse of the tube box to be effected by a hand-wheel, which should not protrude more than 4 to 5 in. Well-separated lever diaphragm controls.

(10) The chassis to be mounted on ball bearings.

(11) A centring device which automatically moves with the tube box but the upright of which does not project more than 3 in. from the table in any position of the tube box.

(12) All-metal construction with provision of an earthing terminal.

(13) The overhead tube box to be totally enclosed and to have an overlapping protection value of 2 mm. of lead. Transverse tilting and raising movements present. Wherever necessary spring buffers. The raising mechanism to be operated from one side. The uprights to be sufficiently wide to allow easily ingress of a Potter-Bucky apparatus and to allow the lateral insertion of plates between the uprights.

The overhead tube-box and undercouch tube-box to be capable of movement along the full length of the table and capable of passing each other.

(14) Automatic balance should exist in all positions of a combined couch and screening stand. The necessity of adding or removing separate counterweights is objectionable, particularly since, if these are forgotten, there is a great risk of sudden movement and resulting fracture of the non-counterweighted tube.

## TUBE STANDS

A few years ago the X-ray tube stand was a cheap inexpensive form of apparatus as shown in Fig. 344, capable of ;

(1) A vertical adjustment by a rack-and-pinion movement.

(2) A similar horizontal movement.

(3) Inclined movements of the tube in the two vertical planes.

(4) Rotational movements of the tube, the chief use of which was to arrange the tube in the most suitable direction for direct connection to the high-tension down leads.

All movements were calibrated. The chief requirements were rigidity and ease of adjustment and, depending entirely upon its use, a certain degree of protection.

As the voltage of operation was increased a need arose for greater protection, but this protection has been afforded without any regard to its particular use.

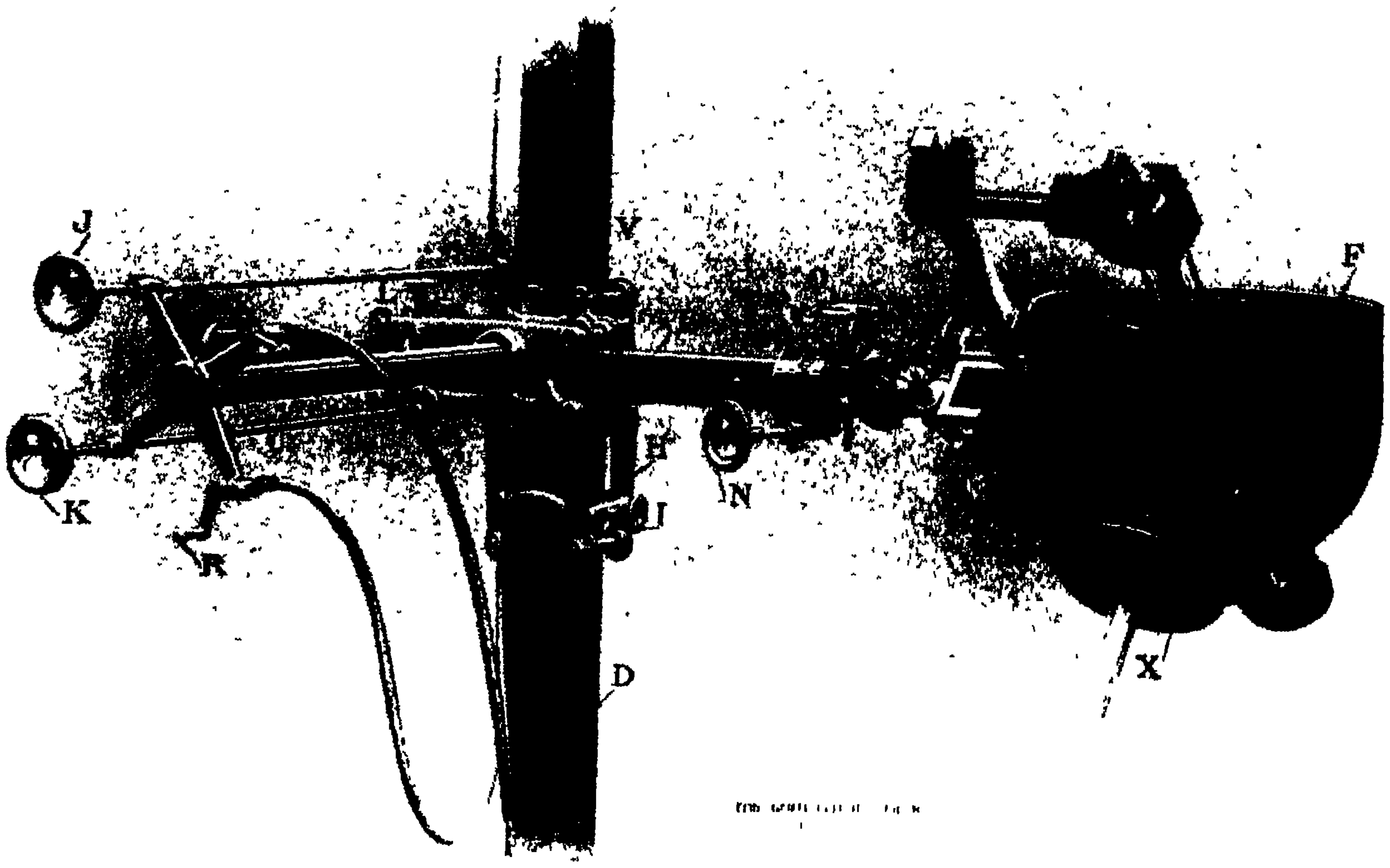



FIG. 345.—Movements of Tube Stand.

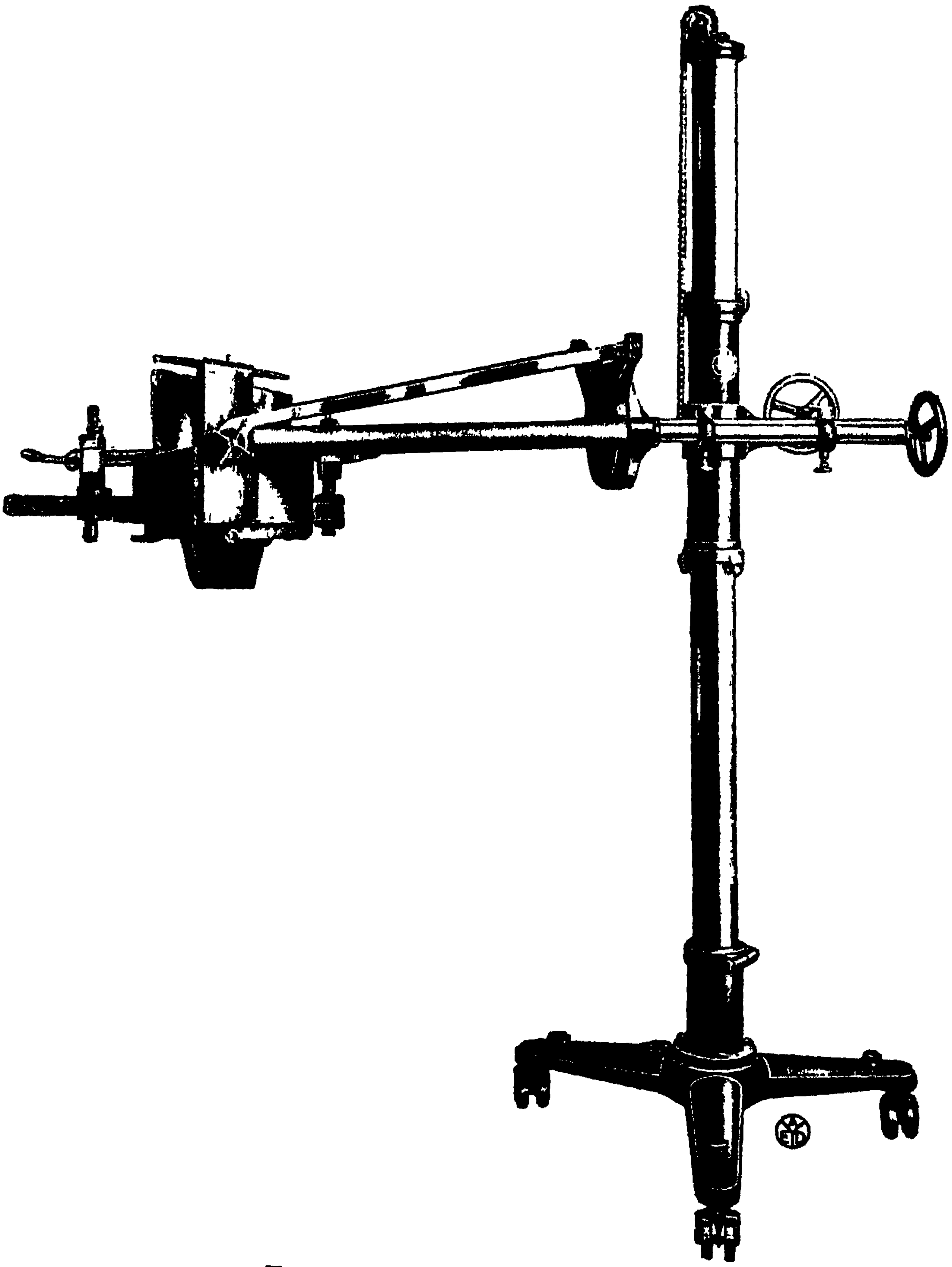


FIG. 346.—Therapeutic Tube Stand.

[To face p. 399.

Such a tube stand is beyond the limits of easy movement of the female operator and, as a result, the tube stand is becoming an obsolete apparatus.

As always, it should be the physician and not the physicist who decides upon the limit of protection and, in a well-protected X-ray treatment department where the operatives are protected by a cheaper barium plaster wall, it is unnecessary for total enclosure of the tube, to be obtained.

Examples of certificated tube stands are shown, but as their cost equals, or is greater than that of a normal couch, it is usually more advantageous to employ a couch which moves the patient instead of a tube stand. For deep therapy the suspended protective tube box with a normal surgical table is preferable.

## PORTABLE APPARATUS

For military purposes during the late war, X-ray installations were installed and transported in motor lorries.

The apparatus itself offers no especial features and was of either the coil or transformer type, but invariably the coil.

In the former type of generator accumulators were used, either charged by the Army Service Corps charging plants, or from a direct-current generator directly coupled by a clutch to the lorry petrol engine. For transformer apparatus the same prime source of energy could be used to actuate an alternator.

The screening stands and couches were of a light collapsible form and would in no way conform with N.P.L. requirements.

Such apparatus is only of interest in military circles. A type of portable apparatus of greater interest in civil radiological circles, is the portable installation used to obtain radiographs in the hospital wards, in cases where patients cannot be moved from bed, for example, fractured femur cases.

Such installations were, until the past few years, merely an induction coil and interruptor mounted upon a trolley (Fig. 271A).

Of recent years this type of apparatus is being replaced by transformer apparatus in which the use of the 30-milliampere self-rectifying Coolidge tube, avoids the necessity of a rectifier. A modern type of apparatus by the same makers of Fig. 271A is shown in Fig. 271B. Essentially it consists of a small oil-cooled transformer unit within a movable cupboard upon which the filament current and transformer resistance coils are mounted. Technically it offers no special features.

The use of a close-fitting glass or other shield reduces the weight of protection necessary for the small 30-milliampere tube, which is supported by a light tube stand fitted to the transformer case (Fig. 347).

(10) Show that the present-day heavy protective tube stand is unnecessary in a properly organised therapy department.

(11) Describe the advantages of the electron tube for portable apparatus.

(12) Discuss the advisability of earthing X-ray apparatus. In a composite wood-and-metal couch and a screening stand, what factors would you consider in earthing the various components ?

vided with stereoscopic stops. The pressure board is fitted into a series of holes running from back to front, which enables the board to be placed in front or behind the patient. The pressure board is provided with a strap for holding the patient against the board.

A willemite screen, 16 × 16 in., covered by a thick lead glass is provided. This screen is supported in a metal frame, into which it fits, and when released will hang downwards. On the back of screen are clips for holding plates or films. Cassettes can be used by detaching the screen and inserting the cassette, or it may be clipped on to the back of the screen.

The framework is all steel, bolted to top and bottom castings. Linoleum is provided for the patient. The moving mechanism runs on ball bearings and the whole is carefully counterpoised. In spite of the weight, it is extremely easy to manipulate.

Insulators are provided for a safe straight feed from the top to the tube, and with two insulators for leading in below.

Connections are made for the standard type Coolidge tube ; but the box may be used for gas tubes by slightly opening the doors at back.

Fig. 350 (*Messrs. Gaiffe, Gallot & Pilon*) shows a very compact type of apparatus, since the high-tension generating plant is included and is placed behind the screen (Fig. 196, Vol. II.). The need of a rectifying disc is avoided by working the electron tube at values for which the tube is self-rectifying.

This construction avoids the use of long high-tension connectors and the whole apparatus is enclosed in an earthed gauze screen behind, completed by a thin aluminium sheet in front of the tube, which also serves to remove the very soft radiation, whilst forming an electrical Faraday cage.

It is arranged that when the door of this cage is open the low-tension circuit is broken, so that the apparatus cannot be touched whilst alive. The controls are mounted to the left of the screen and are conveniently situated for the operator.

Fig. 351 (*Messrs. Keeley-Koett, U.S.A.*) shows an extremely compact form of screen and the figure illustrates how abroad, for low-voltage radiography, the large and cumbersome tube box is replaced by a closely mounted protective but insulating shield, so allowing the need of heavy counterweight mechanism to be avoided. An oblique movement in the vertical plane is provided by means of a swivel above. As the protection extends beyond the diaphragm aperture protection this is permissible.

The perfect semi-rigid method of screen suspension, makes it possible to swivel the screen to conform to the contour of any surface and yet let the rays follow it in every direction when moving it about ; the tube target is always aligned with the screen.

Ball bearings are used throughout its construction thereby permitting almost frictionless adjustment during fluoroscopy. The screen and X-ray tube move with the slightest pressure. The dual diaphragm controls are conveniently located for easy and accurate manipulation.

Levelling screws are part of the base equipment. After the fluoroscope is rolled into place, it may be solidly and permanently fixed by turning down these screws, thus raising the castors off of the floor.

Fig. 352 (*Messrs. Newton & Wright*). In this screening stand the whole mechanism is carried on a single pair of uprights, thus avoiding the boxed-in

weights running over grooved ball-bearing pulley wheels and in addition, the movable frames are guided by ball-bearing wheels also.

It is possible, within limits to regulate the distance between the tube target and the fluorescent screen by releasing two handles immediately below the cross bar on which the firm's name is engraved, sliding this backwards or forwards as the case may be, and locking it by turning the aforementioned handles.

The vertical movement has a range of 39 in. and the maximum height attained by the target of the tube is 5 ft., giving a diagnostic height of 5½ ft., while the transverse movement is 15 in., thus giving a total area of 39 × 15 in. at any point to which the central ray can be placed.

With regard to protection, the tube box is covered entirely with 3 mm. of lead and totally encloses the X-ray tube, while, although not shown in the picture, aprons are hung round the fluorescent screen and sides of the screening stand, fully affording protection as stipulated in the X-Ray and Radium Protection Committee's reports.

## II.—COUCHES

Fig. 355 (*Messrs. Acme International Co., U.S.A.*). A well-designed table in which the small tube container and the protected down leads should be noted.

There is protection from any liability of shock in the form of a metal guard encasing the lower portion of the terminals.

The screen frame is adjustable for practically every conceivable angle and is held rigid in place at all times by means of friction joints.

A tube shield for enclosing either a radiator type tube or a 7-in. diameter bulb tube is furnished with the fluoroscopic unit. A shield for enclosing the radiator type tube only can be furnished.

Fig. 356 (*Messrs. Cox-Cavendish Co., Ltd.*). The framework of this couch is of steel tubing fitted into oak ends. A tube box, covered with 2-mm. sheet lead, is suspended from a carriage mounted on ball-bearing rollers so that it moves freely in longitudinal and transverse directions. All metal parts of the couch are connected electrically, and by use of a simple "earthing" device no leakage of current can be felt on touching any part of the couch.

To this same carriage is fixed an apron board, also lined with 2-mm. lead, which, being interposed between the operator and the tube box, forms a second protection in addition to that already offered by the tube box itself. A lead-backed mirror in the apron board, opening to an angle of 45 degrees enables the operator to examine the X-ray tube through a lead-glass window in the tube box without stooping down or exposing himself to the rays.

The high-tension leads are taken from one end only, thus leaving both sides and the foot of the couch quite free. Both leads are conducted through thick insulating tubes, each tested to stand 14-in. spark potential, which prevents sparking to frame or tube. Special arrangements are made for the accommodation of the Coolidge tube, so that when it is used no further wires are necessary for carrying the heating current to the filament. In the side of the tube box is a lead-glass window, directly opposite to the mirror in the apron board and provided with cross marks for centring the tubes.

The movement of the tube box is controlled by means of a wooden handle which projects beyond the apron board, and on this are arranged the levers

known as a convertible couch and screening stand but is rather a couch with a screening stand attachment.

Fig. 362 (*Messrs. Watsons & Sons, Ltd.*). The construction of this instrument is carried out in polished mahogany and nickel-plated steel, while the tube box is totally covered with metallic lead well above the minimum limits advocated by the X-Ray and Radium Protection Committee. Briefly the construction is as follows ;—

There are two mahogany end frames linked together by four steel tubes. On the upper two steel rails a carriage runs from end to end of the couch and is mounted on ball-bearing wheels. On this carriage there are two rails carrying the second carriage, on which is mounted the tube box. A locking system is provided for the lateral and transverse movements of the trolleys. The lateral movement is scaled, and when working in conjunction with a scaled plumb-bob system over the couch the position of the central ray is always indicated. The diaphragm attached to the tube box is rectangular and the two sets of shutters are independently controlled.

The couch top rests upon the end frames and is easily removable whenever necessary. All woodwork which is liable to be interposed between the X-ray tube and the patient is X-rayed before any attempt is made to construct the couch, with a view to eliminating knots and metal filings, etc., from the three-ply used for this work.

The high-tension system is arranged as shown through one end of the couch only, and is conducted from a height of 7 ft. through stout ebonite insulators to prevent direct accidental contact with the high-tension wires, and these insulators terminate with suitable spring tapes for connecting to the tube box. An automatic system is provided on the tube carrier which slides inside the box for making the contacts to the high-tension circuit. When the overhead system is adopted in addition to the undercouch system, extra rails are provided on either side of the couch top, on which the system as shown in the inset picture runs. The overhead tube carrier has a stereoscopic shift movement in addition to the lateral and longitudinal movements.

Fig. 336, page 393 (*Messrs. X-Rays, Ltd.*). This couch is designed mainly for screen examinations but can, of course, be used for radiography if desired. The framework is of wood with a polished three-ply top which has an independent raising and lowering movement at each end of the couch, having a range of 10 in. A greater range than this can be fitted if desired.

The tube box is of the totally enclosed type protected by lead and lead rubber, giving a total protection equivalent to 3 mm. of lead.

The diaphragm is a square pattern surrounded by a cone to suppress stray radiation.

The tube box is ventilated at the ends and the ends are insulated with paxolin and lead rubber, and carry the terminals for connection to the tube. The whole of one side of the box is removable for insertion of the tube. The tube box is mounted on ball bearings on a carriage which has cross movement and full movement up and down the couch. Attached to this carriage is a wooden screen lined with lead, through which project the two handles for controlling the diaphragm, and a third handle for controlling the cross movement of the tube box. Attached to this handle is an indicator which may be set at any position, and which shows the necessary shift for stereoscopic work.

The protective shield is carried unusually high to allow for the tilting top

Fig. 365 (*Messrs. Gaiffe, Gallot & Pilon*). This combined couch and screening stand may be used as an upright screen, and as a couch for both undercouch and overcouch tube work, in the latter respect differing from many similar apparatuses. A single tube permits of these three uses. The table is of the gantry type and is converted from a table to a vertical stand by drawing the table forward and then swinging it up and backwards. It is for Coolidge tube working only. The screen is held in a triple articulated arm which permits its use in any of the desired positions (Fig. 322).

Fig. 366 (*Messrs. Keeley-Koett, U.S.A.*). This apparatus permits examination in any position from the vertical to the Trendelenburg position.

It is distinctive in being motor driven, with a convenient switch control located on the fluoroscopic screen carriage. The motor is instantly reversible.

The X-ray tube moves in unison with the fluoroscopic screen lengthwise of the table and crosswise individually. The moving parts are accurately counterbalanced in all positions, so that the hands are left free for fluoroscopic examination. Ball-bearing rollers are used so as to permit frictionless manipulation.

An adjustable conveniently controlled lead diaphragm allows the operator to select any size screening area desired.

An overcouch tube stand is provided.

Fig. 367 (*Messrs. Siemens & Halske*). This was one of the earliest combination apparatuses and has been much used. Of special notice is the telescopic attachment for orthodiagraphy of the heart, etc. This extends the tube and screen distance to 9 ft., when the projection is practically parallel. The danger of such a method is that the operator then stands in the projected rays, unless a separate portable screen is used, as is easily possible. This apparatus allows very many different operations as are evident from the illustrations.

Fig. 368 (*Messrs. Viefa-Werke*). This apparatus is intended for diagnostic work and surface therapy. With it all fluoroscopic and radiographic work with a standing or reclining patient can be undertaken.

It can be seen from the illustrations that the universal combined apparatus consists of a supporting stand with a fluorescent screen and cassette holder movable in all directions, an exposure couch, and a tube stand which can be easily pushed alongside same and brought into any position desired at the moment.

The apparatus can be used for the following purposes ;

(1) Fluoroscopy with standing or sitting patient.

(2) Radiography of sitting or standing patient at distances of from 60 cm. to 2 metres (for teleradiography).

(3) Radiographic work of all kinds on a recumbent patient from above and from the side.

(4) Fluoroscopy and radiography from below with the patient lying in any position.

(5) Stereoscopic exposures in any position, lying or sitting.

(6) Orthodiagraphy on a standing, sitting, or recumbent patient.

(7) Surface irradiations of all kinds.

Fig. 369 (*Messrs. X-Rays, Ltd.*). A combination of the turntable type.

This combined couch and screening stand has been designed with a view to supplying a unit which affords ample protection, and may be used with either

The front aperture of the shield is fitted with a pair of slides into which any standard diaphragms or treatment applicators may be fitted.

Fig. 372 (*Messrs. Reiniger, Gebbert & Schall, Germany*). A similar simple apparatus for undercouch work, consisting of an upright guide frame on which rests a carriage provided with ball bearings, which is movable along the length of the couch.

For moving the box sideways a cross arm is fixed to the carriage, and here also ball bearings are provided.

The apparatus is not in any way fixed to the couch, but can be easily pushed under the same. It serves for fluoroscopy and photography from below. An upright column fixed to the cross arm is provided with holder for the fluorescent screen, which may be interchanged at any moment with a cassette holding a photographic plate, so that a photograph may be taken immediately after fluoroscopic examination.

Fig. 373 (*Messrs. Solus*). A further " N.P.L." tube stand, the noticeable feature being the neat method of counterpoising the heavy tube box.

The tube box gives a total protection of 2·5 mm. of lead, and can be used for either gas or Coolidge X-ray tubes. This tube box of necessity weighs about 50 lb., and in consequence, it is difficult to design a tube stand that can be easily operated in all directions without overbalancing.

The tube-stand movements are all on ball bearings, and every moving part is counterweighted, which means that the tube box can be operated with the least exertion. The weights that counterbalance the tube box are fitted in such a position that they balance the box, whichever way it is rotated or moved. An adjustable friction clutch is provided for obtaining final fine adjustment of the tube-box carrying-arm counterweighted mechanism. This whole mechanism, when finally adjusted for treatment, can be locked in that position, and must be unlocked before it can be again moved. Stereoscopic movements are provided on the tube box, and final microscopic adjustments for centring can be made on the tube-box carrying arms.

The illustration clearly shows the various other movements and the up-and-down double counterweight system. The whole stand moves on four castors which are fitted into a very heavy large base, and the stand can be rotated in this base.

Fig. 374 (*Messrs. Watsons & Sons, Ltd.*). This tube stand is constructed entirely of metal with the exception of the tube grips, which are made of fibre fitted with rubber clamps. The movement carrying the tube is counterbalanced so that adjustments are made with the minimum expenditure of energy, and are facilitated by two handles, one fitted directly to the movement and the other attached to the pulley wheel over which the Bowden cord runs.

The tube stand is mounted on a large tripod foot, and adjustments in the horizontal plane, using the central pillar of the tube stand as its axis, are possible. A stereoscopic shift is arranged for and all possible angling movements, including circular movement, in parallel with the axis of the tube itself.

For treatment purposes, an extra movement is provided which allows of the tube being angled so that anode and cathode ends are oblique to the horizontal axis of the tube.

The apparatus is finished in nickel plate and grey enamel.

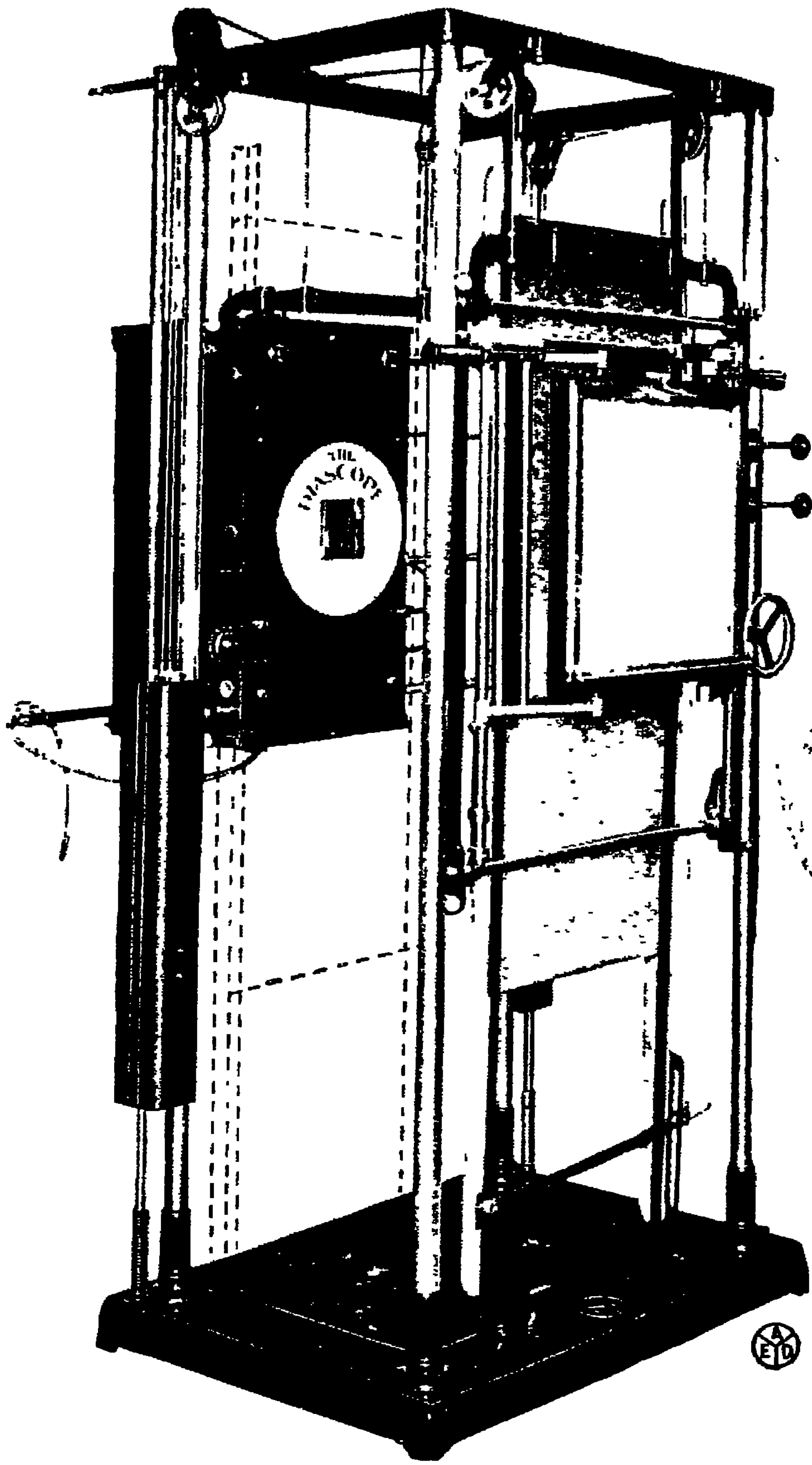



FIG. 349.—Screening Stand (Messrs. A. E. Dean & Co.).

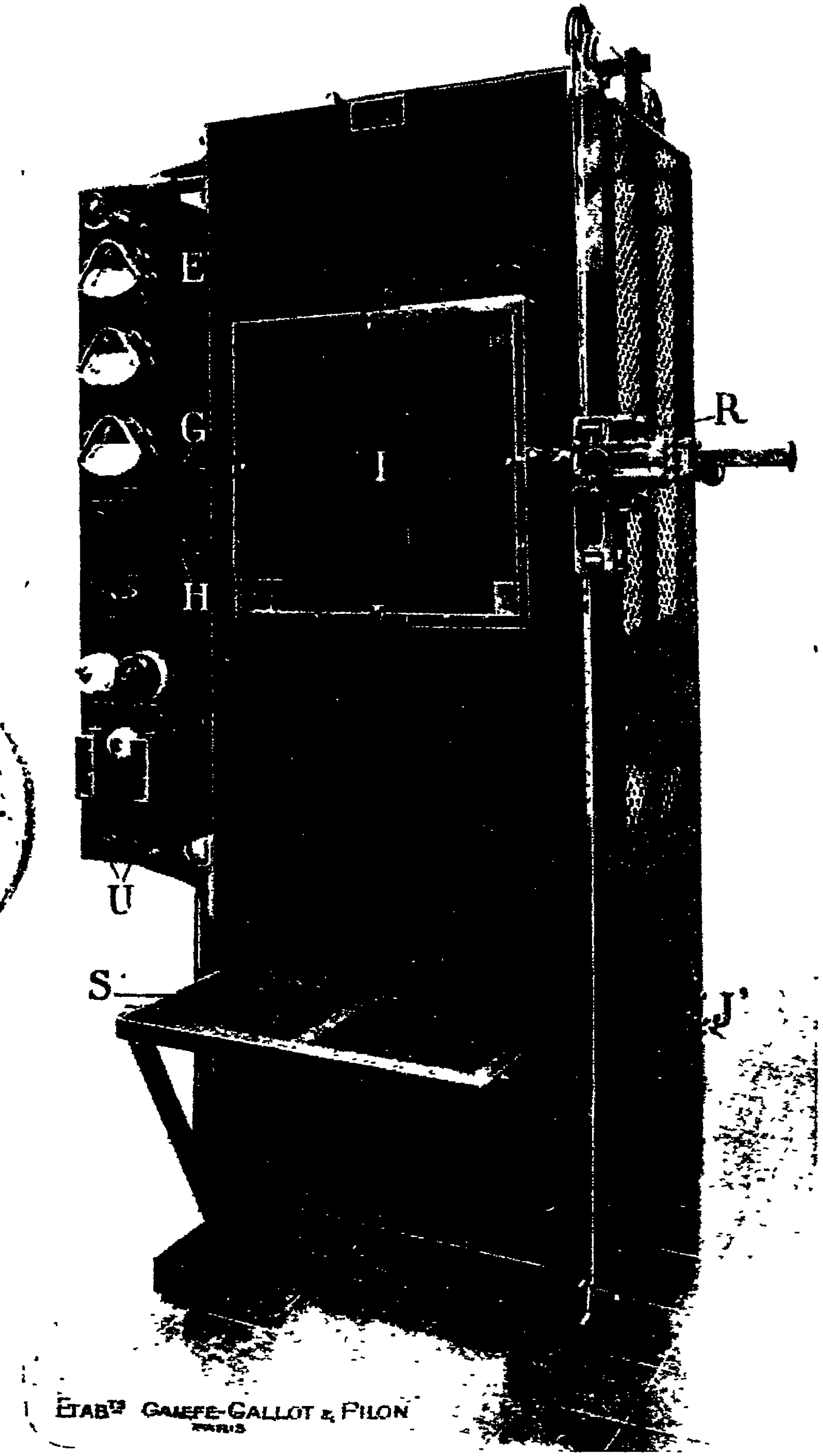



FIG. 350.—Screening Stand (Messrs. Gaiffe, Gallot & Pilon).

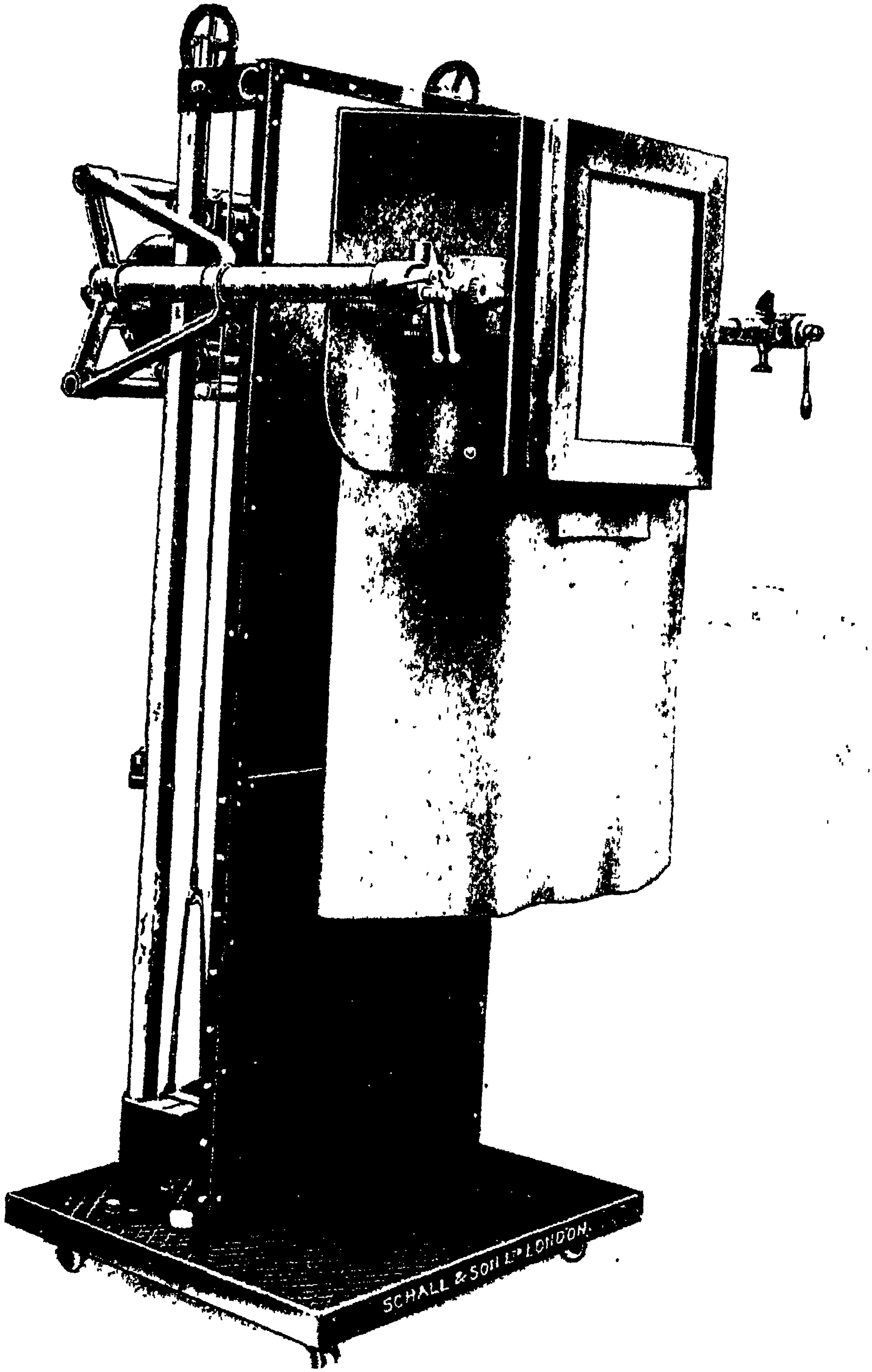



FIG. 353.—Screening Stand (Messrs. Schall & Son).

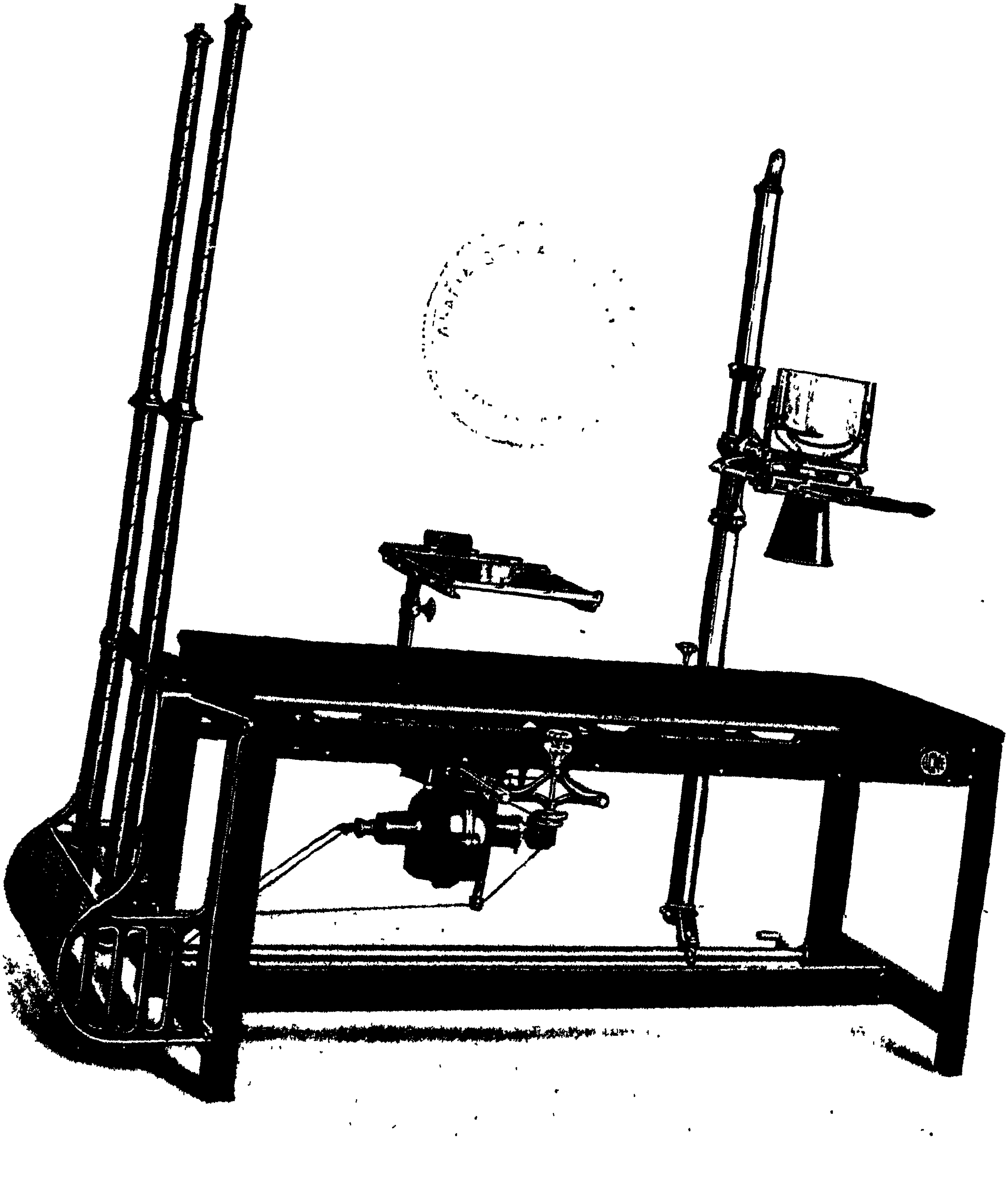


FIG. 355.—Couch (Messrs. Acme International, U.S.A.).

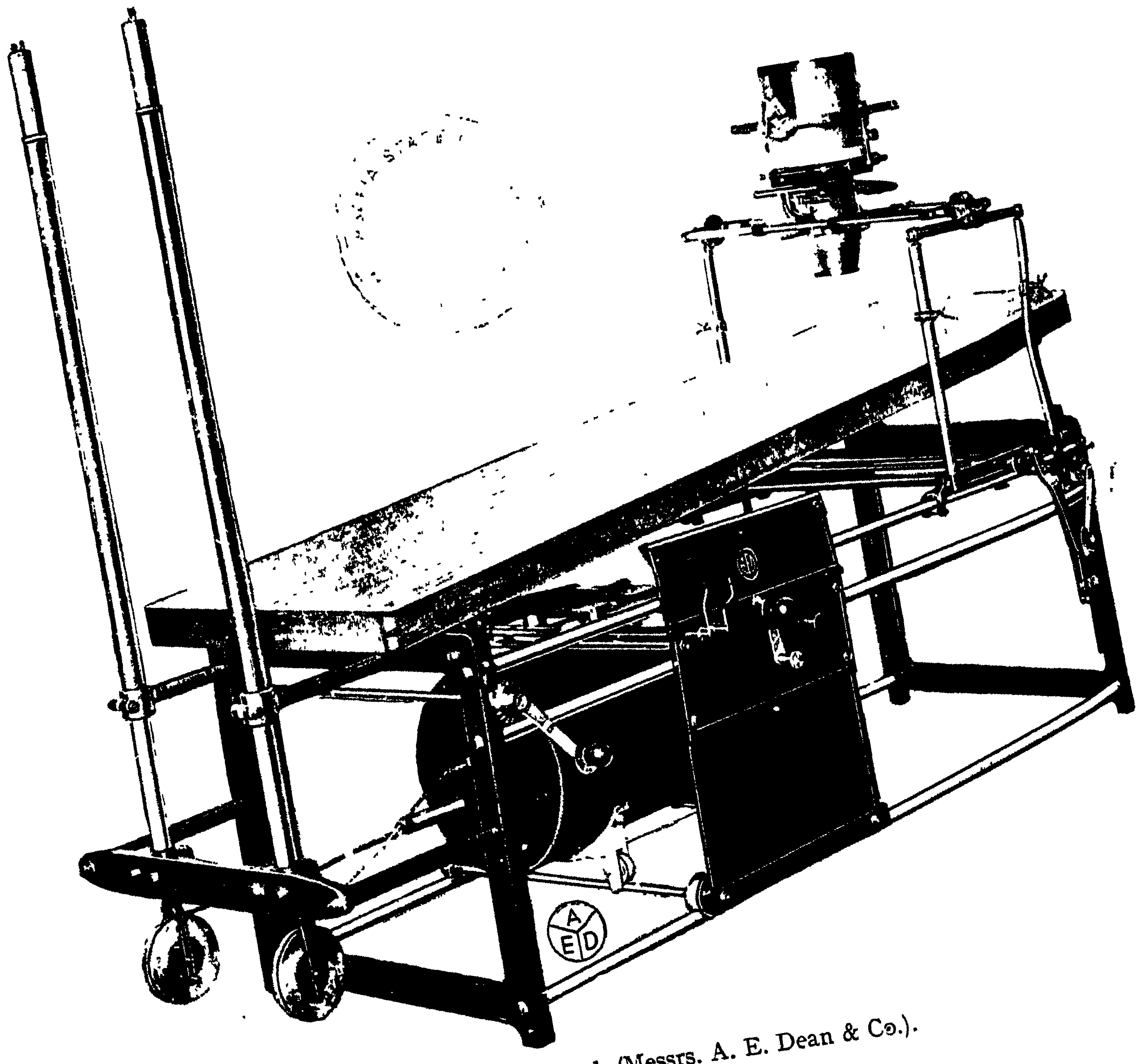


Fig. 357.—Couch (Messrs. A. E. Dean & Co.).

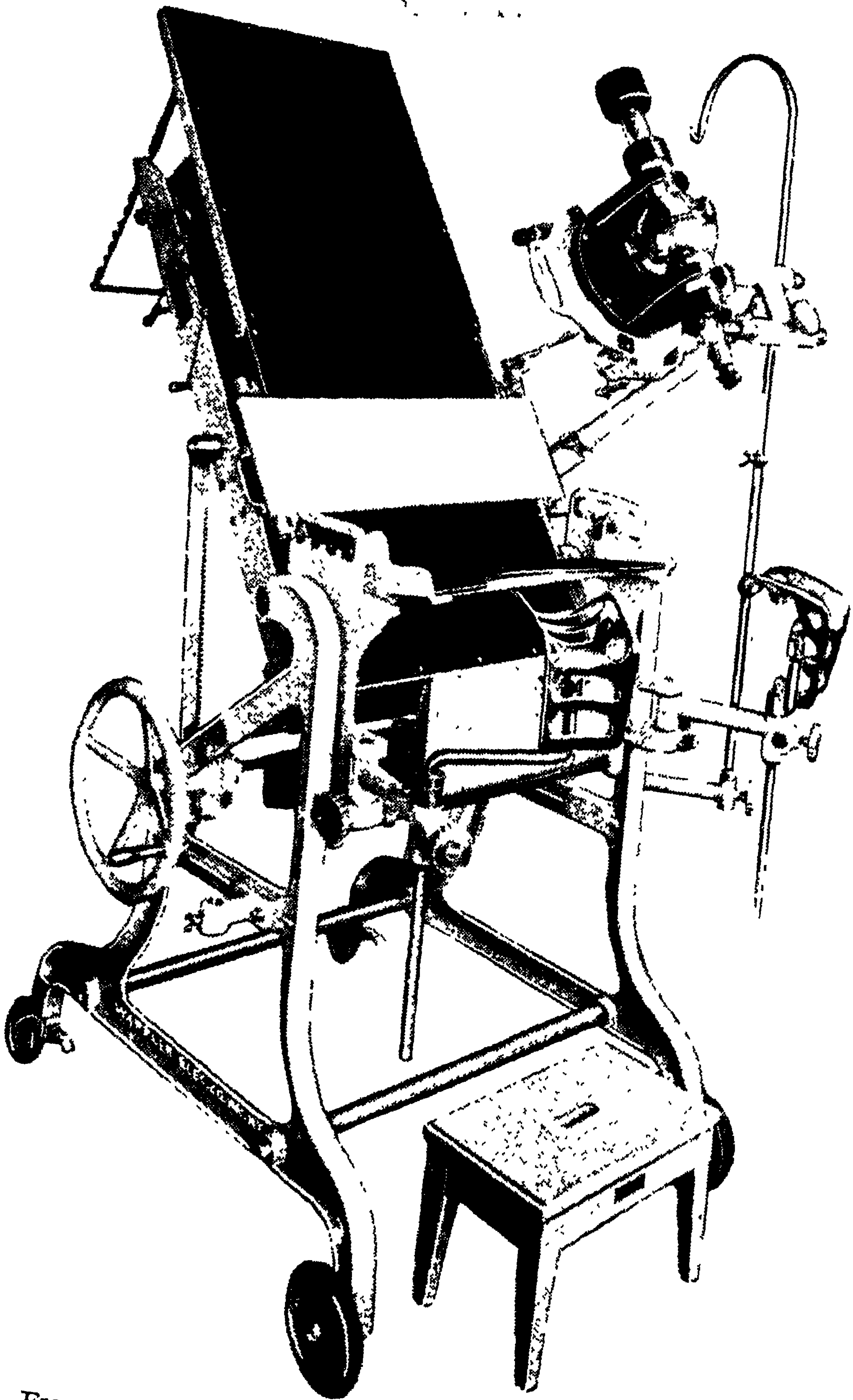


FIG. 360.—Cystoscopic Table (Messrs. Wappler, U.S.A.).

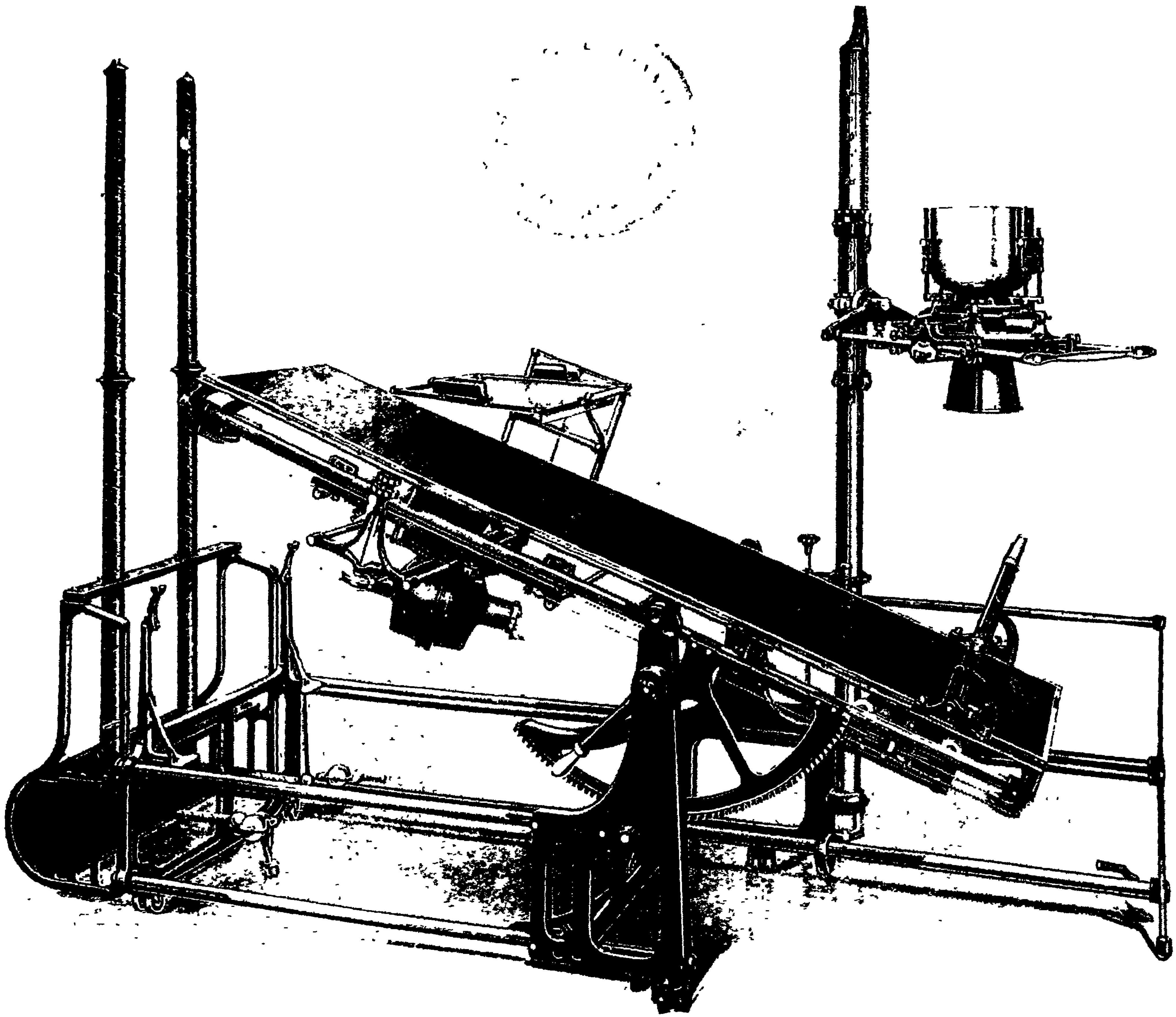


Fig. 363.—Combined Couch and Screening Stand (Messrs. Acme International Co., U.S.A.).

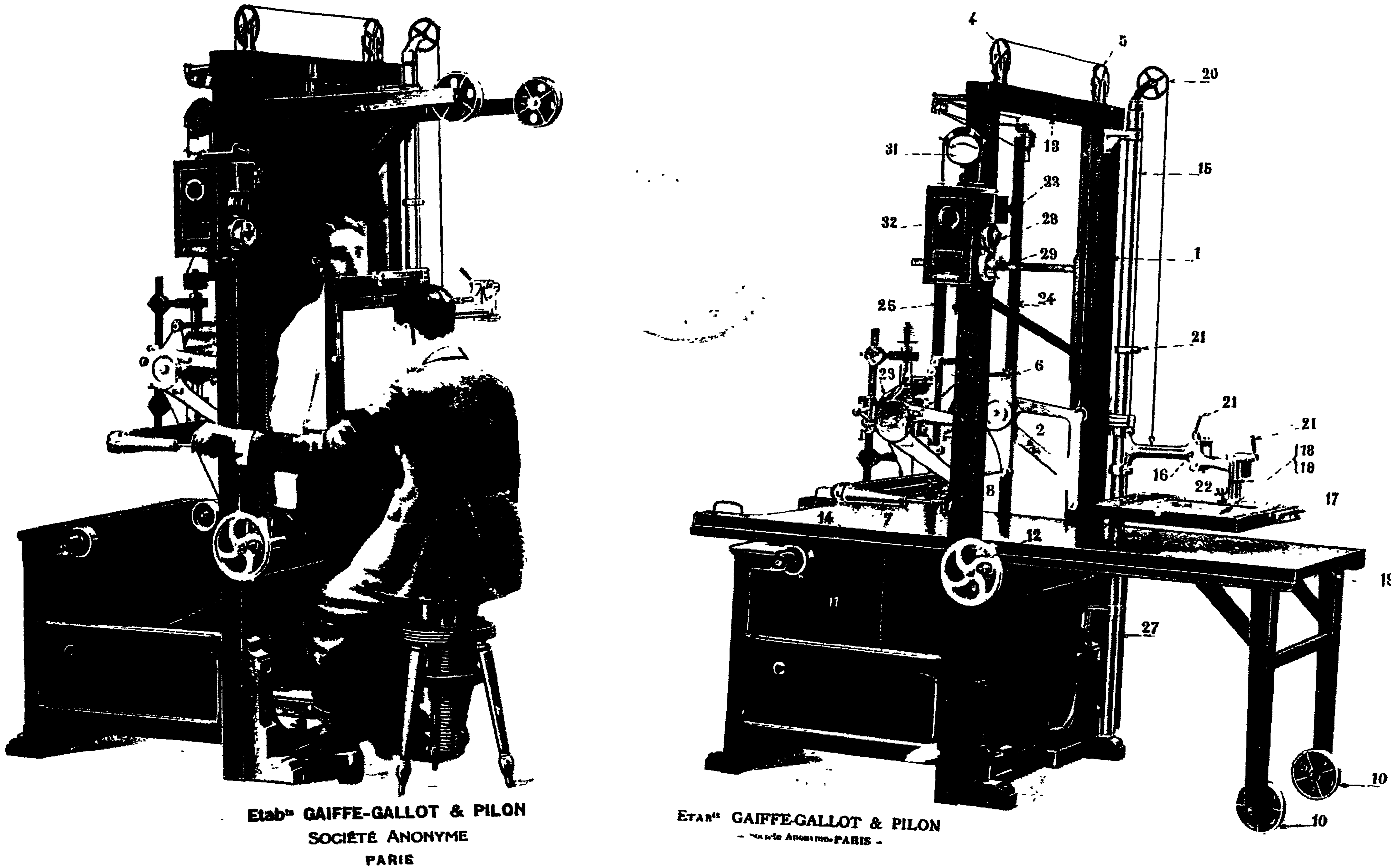
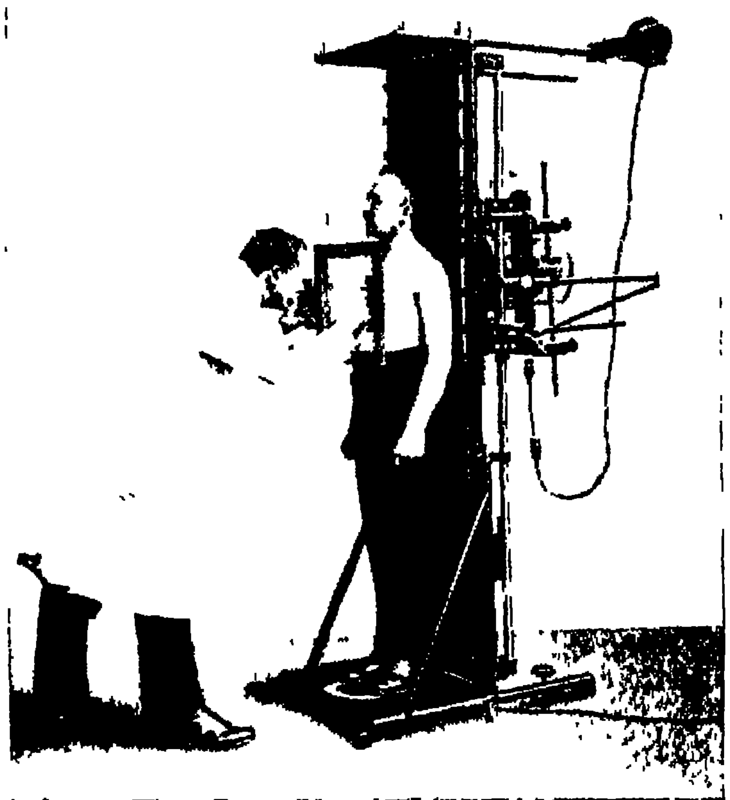
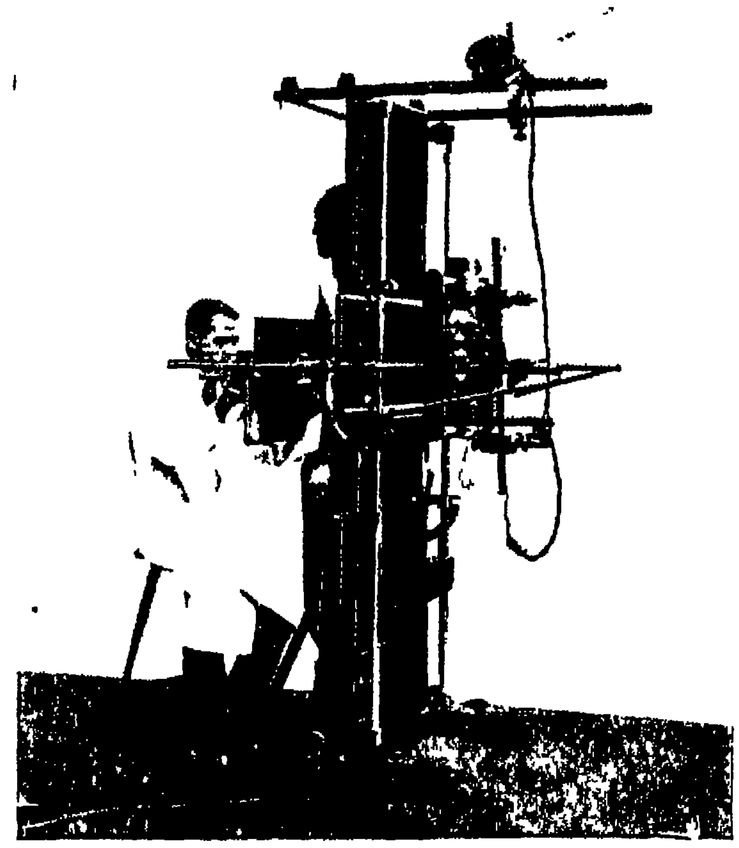


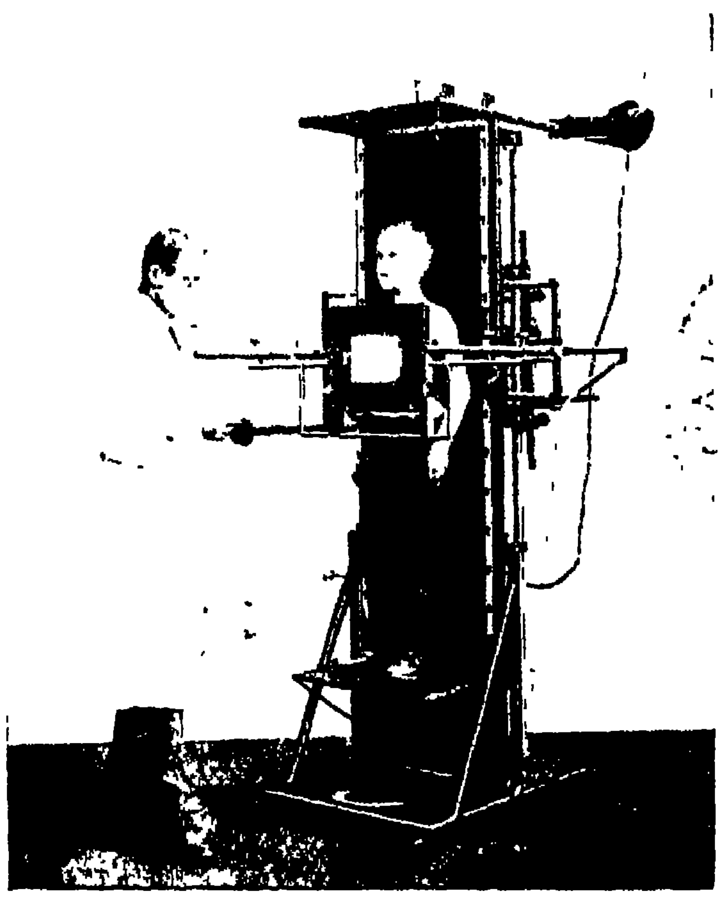

FIG. 365.—Combined Couch and Screening Stand (Messrs. Gaiffe, Gallot & Pilon, France).



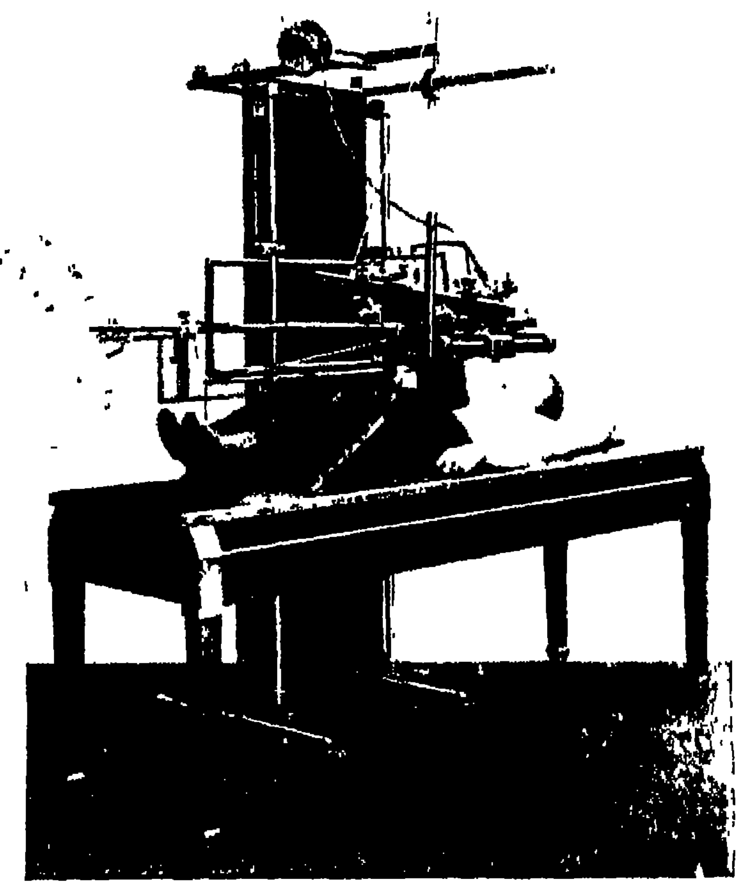
Screening Thorax in Upright Position. The screen is suspended.



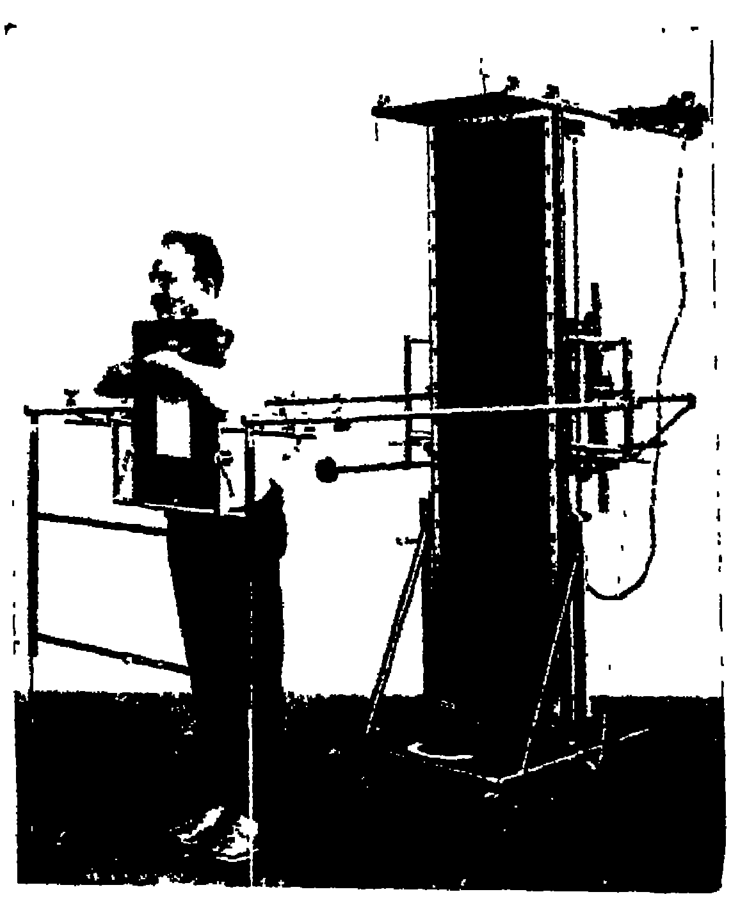
Using the Bucky Grid for Fluoroscopy.



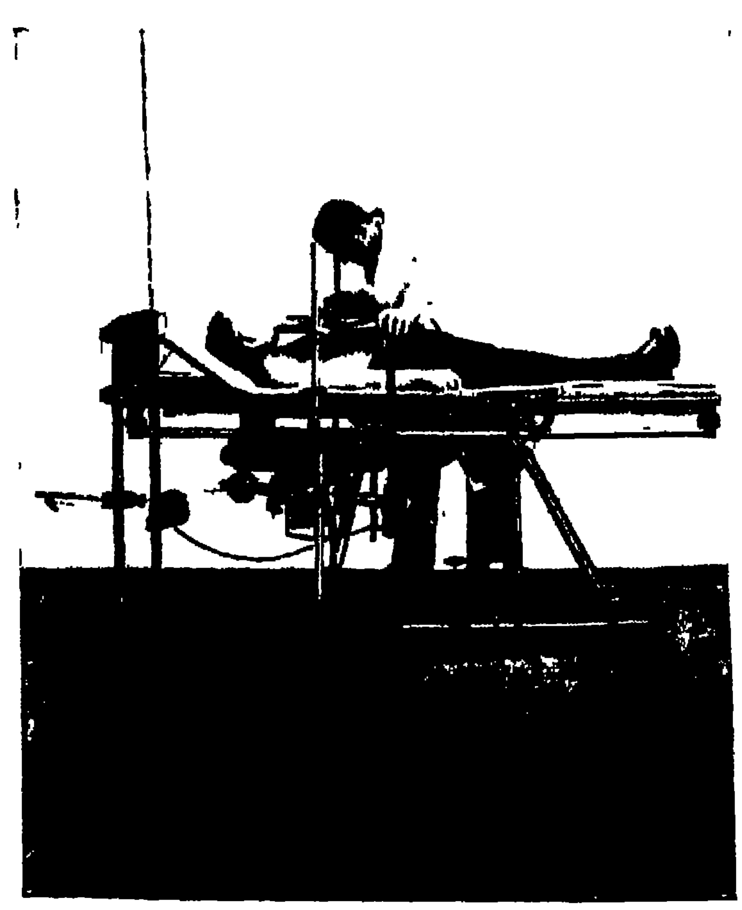
Showing Seat Provided to Screen Children.



Radiography of Kidneys.



Orthodiagraphy Attachment.



Use as Trochoscope to Determine Size of Heart, etc.

FIG. 367.—Combined Couch and Screening Stand (Messrs. Siemens & Halske).

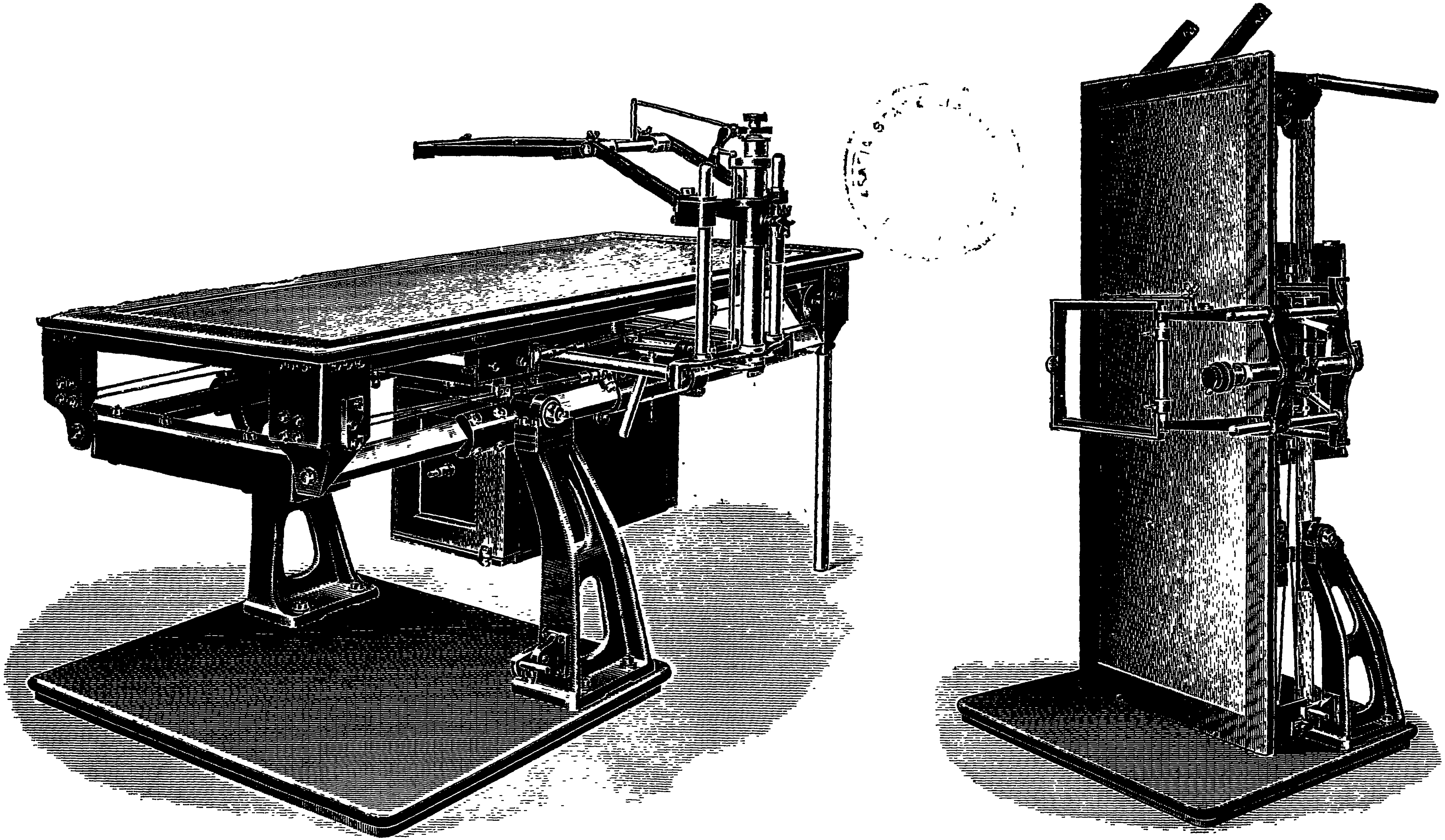


FIG. 369.—Combined Couch and Screening Stand (Messrs. X-Rays, Ltd.).

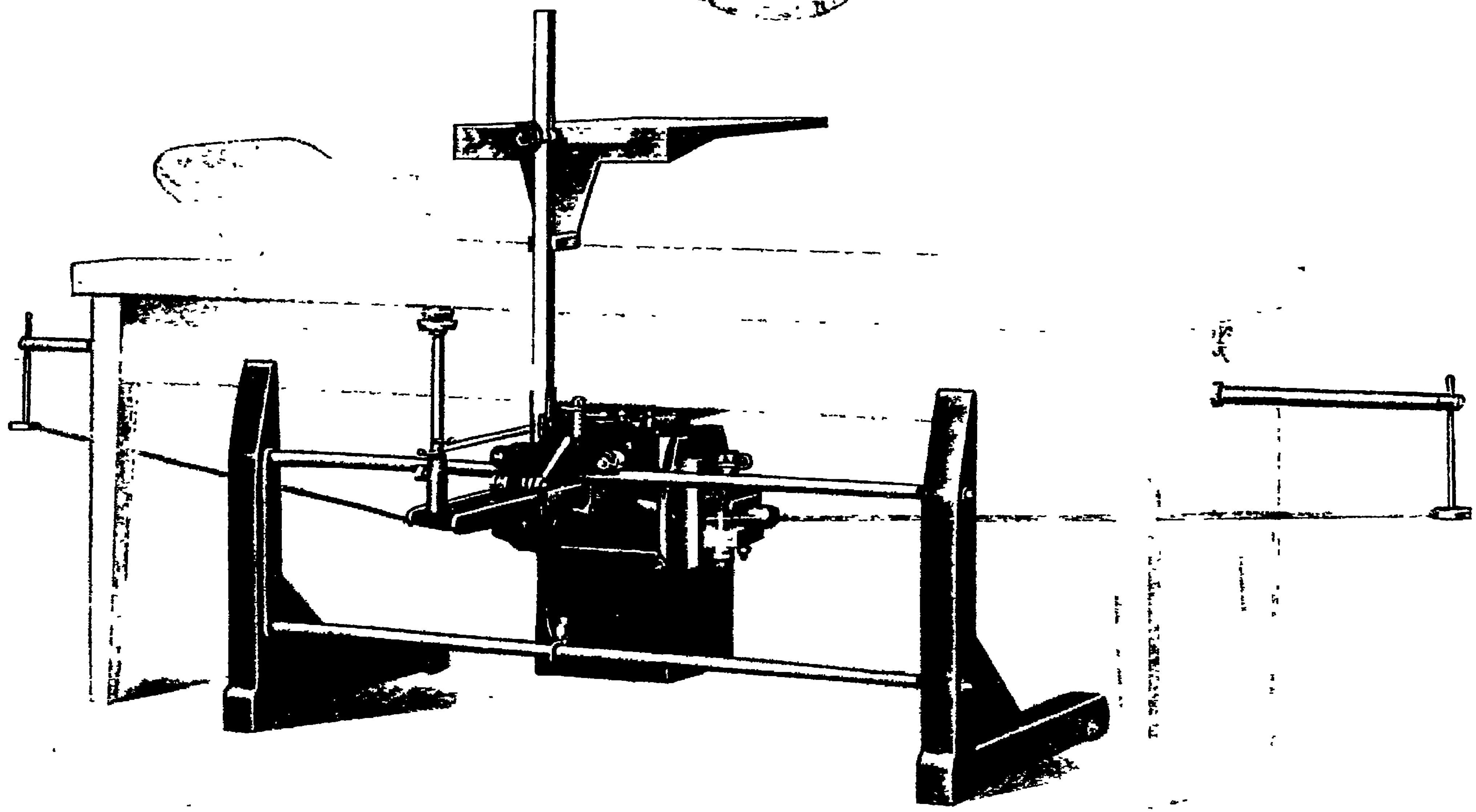


FIG. 372.—Rail Mounted Tube Stand (Messrs. Reiniger, Gebbert & Schall).

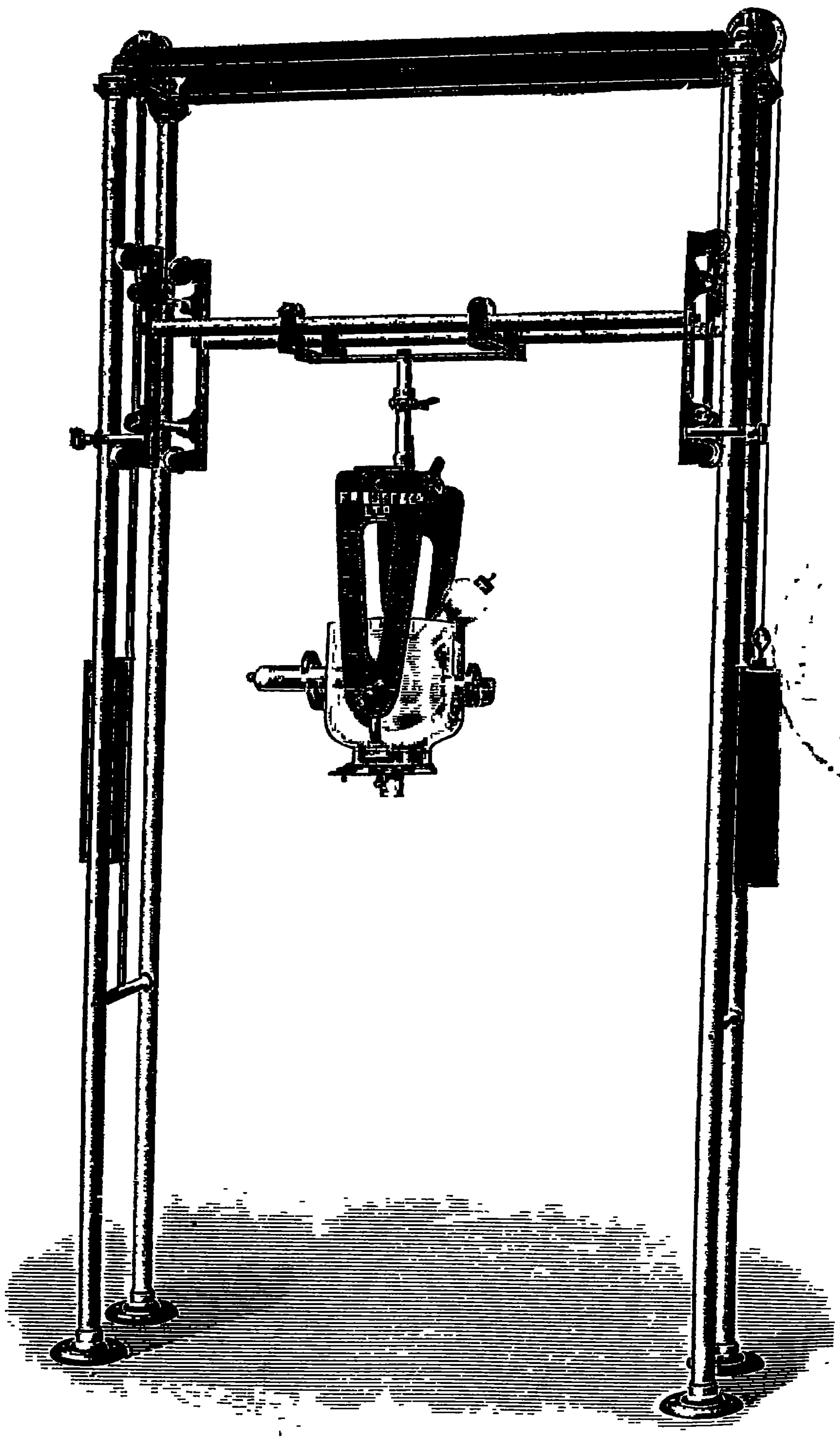


FIG. 376.—Overhead Tube (Messrs. X-Rays, Ltd.).

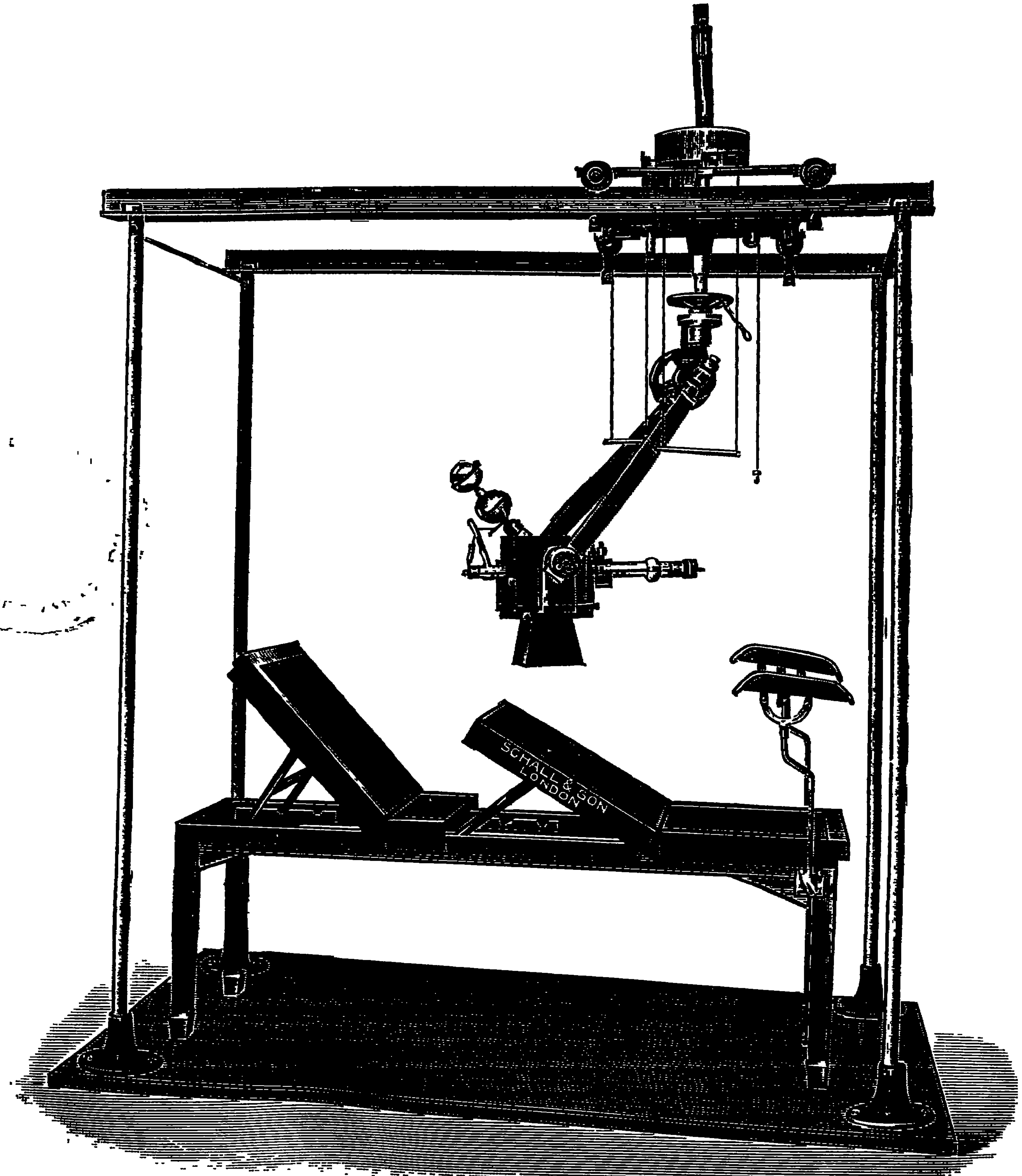



FIG. 377.—Overhead Tube (Messrs. Schall & Son).

# CHAPTER IX

## ACCESSORY APPARATUS

### THE VIEWING BOX

THIS is a small but necessary apparatus, to allow plates and films to be viewed by a comparatively strong transmitted light. It is simply a box with a frosted glass window to diffuse the light of one, or more, electric lighting bulbs within it. A more homogeneous field of light is obtained, if the actual bulbs are not within direct view *viâ* the window, but throw light upon a suitably disposed white plane reflecting it towards the window.

A resistance should be fitted in the lighting circuit to allow the intensity of the light to be varied at will. This resistance should be of the sliding type to allow a continuous variation of current and resulting light intensity. As the instrument is often switched on in the dark the switch should be protected to prevent direct contact of the hand when seeking for the switch.

Since the detail of plates or films is rendered much more evident when placed in a viewing box, than when merely held up to the light, a viewing box should be placed in every hospital ward for the use of the physicians. The cost is not great and, given a sample, any joiner or tinsmith will construct a number at very small cost.

As films are liable to stick to the glass, particularly when this is warm, a small fillet of wood should be placed to render this impossible.

The most simple form is merely a window (Fig. 378) upon which plates of various sizes are placed. The detail is much further increased if all the surrounding luminous area of the screen is stopped down.

This may be done by means of frame diaphragms. In practice, these diaphragm adapters insist on sliding out and, a much better method, is to have two movable blinds as in Fig. 379, which allow any size or shape of rectangle to be obtained. Four blinds (Fig. 380) may be provided, if required, to bring the film or plate in the centre of the box, but this is hardly necessary.

An apparatus to view dental films is much used in America which is merely a projection apparatus, a strong lamp behind the film illuminating this and the illuminated image is viewed by a magnifying lens. In America, where it is not uncommon for the patient to be also initiated into the diagnosis of actual or supposed pyorrhœa, the film may be actually projected upon a magic lantern screen for demonstration by a pointer.

cause accurate overlapping of the images seen in the mirrors. The mirrors are also capable of movement to and from the eyes for the same purpose.

The Wheatstone form of stereoscope does not need further description. The two viewing boxes of which it is composed should be of the roller blind type, and the intensity of illumination of each separately adjustable.

The normal type of stereoscope is shown in Fig. 382, in which the movements are simply obtained by sliding the viewing boxes or mirrors.

A more elaborate form is shown in Fig. 383, in which these movements are made automatically and provision is also made for tilting, rotational and vertical movements. Light shields are fitted so that light from the viewing boxes does not pass to the eye until after reflection at the mirrors.

The limitation of this type of stereoscope is that it is impossible for two persons to view the plates simultaneously. Demonstration of some particular feature, by, say, the radiologist to a surgeon, is not so easily facilitated when each has to view separately in turn.

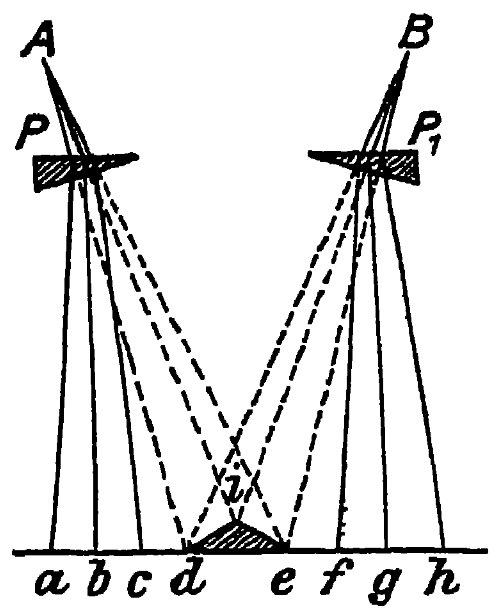


FIG. 386.—Optical System of Pirie Stereoscope.

Duplex stereoscopes (Fig. 384) have therefore been devised, in which two persons can view simultaneously, whilst each can separately adjust his own mirrors to give the best effect without interference with the other observer. Discussion of the particular plate is therefore facilitated.

A very simple form of stereoscope is that of Polack, in which the plates are viewed from the vertical direction, without artificial light, and are merely laid upon a table and adjusted by hand.

A very useful form of pocket stereoscope is that of Pirie (Fig. 385), in which the two stereoscopic plates are viewed at a distance of about 3 to 6 in. by means of a binocular arrangement, one limb of which, to give the correct superposition of images, has a refracting prism.

An optical system by which this superposition of images can be obtained is shown in Fig. 386, where the objects *abc* and *fgh* are superimposed by the prisms P and $P_1$ to give the " solid " image *die*.

It is a simple matter of optics to show that for this result one and not two prisms will suffice, and actually the Pirie stereoscope only employs one such prism, one eyepiece being open.

In France a double-lens instrument of this type has been used by Mattey, and in Germany a similar system is employed in the Gillet stereometer (*q.v.*). A well-known stereoscope, much used for military purposes on account of its small size and portability, is that of Hirtz (Fig. 387), the superposition of which depends on the reflection of one radiograph by a mirror, self-explanatory from Fig. 388.

to be viewed by a particular eye, and in order for this to occur we must introduce some form of shutter device which only allows alternate vision to each eye but at a rate such that owing to the persistence of vision, a permanent mental effect is produced:—

This has been obtained by the following arrangement.

Fig. 389, *a*, shows the tube T in one position, giving a shadow $S_1$ of the object O when viewed with the left eye only, and Fig. 389, *b*, the other tube position in which the shadow $S_2$ is viewed by the right eye only. D is a shield with an aperture which may be brought in front of either eye.

If $S_1$ and $S_2$ alternate sufficiently rapidly upon the screen and if the distance between them is small, then owing to the persistence of vision, if the alternations are sufficiently rapid they may be blended by the eyes into one stereoscopic picture. The eyes may be conveniently alternately exposed by rotating the disc D in its own plane so that the aperture comes opposite to each eye in turn.

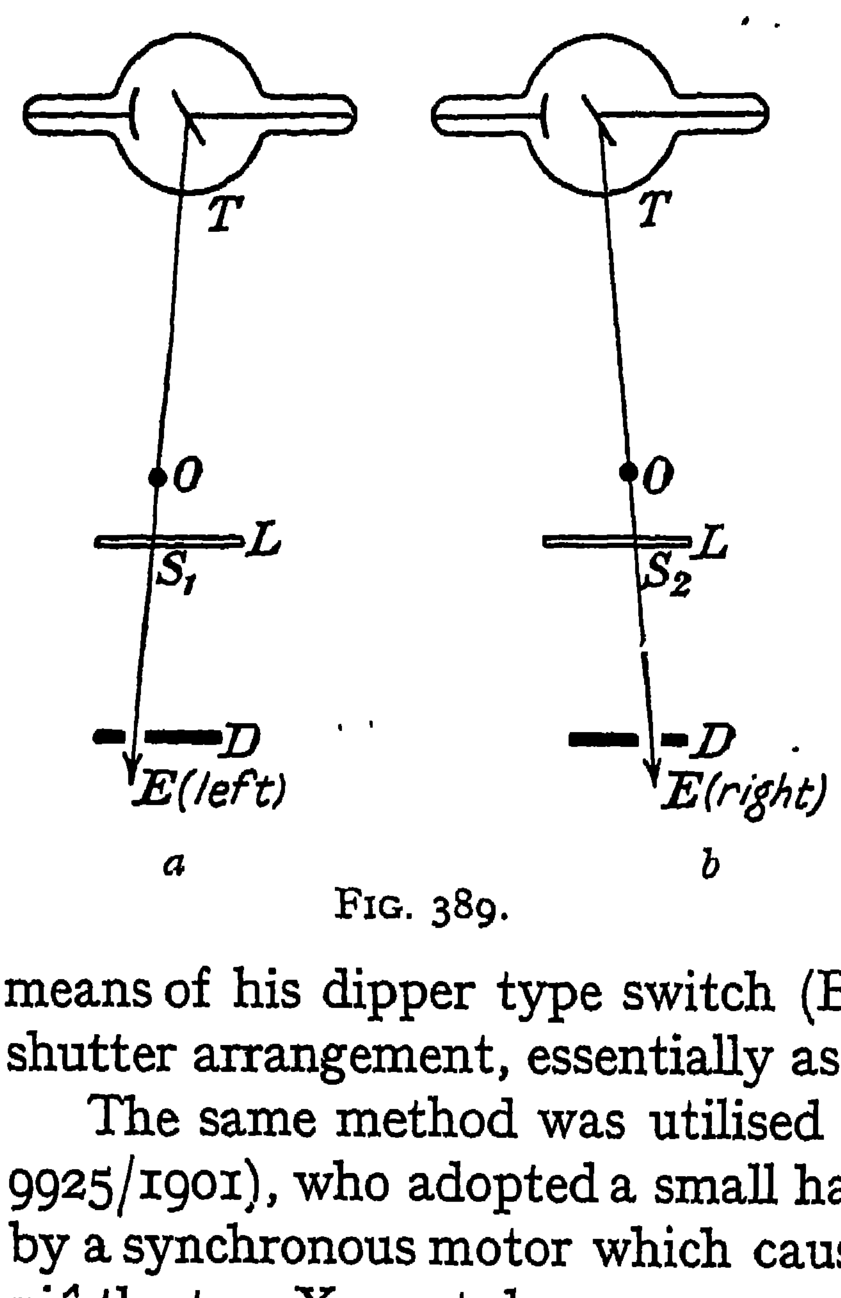



FIG. 389.

The most important point in the design of an actual stereo-fluoroscope apparatus lies in the method adopted for the production of the rapid alternation of the pictures $S_1$ and $S_2$.

This method appears to have been proposed by J. M. Davidson as early as 1899 (Brit. Patent 8934/1899), who used two tubes operated by two separate induction coils alternatively excited by means of his dipper type switch (Brit. Patent 8202/1902) with an optical shutter arrangement, essentially as Fig. 389.

The same method was utilised by Newton and Wright (Brit. Patent 9925/1901), who adopted a small hand shutter as later illustrated, worked by a synchronous motor which caused the make and break of the current *viâ* the two X-ray tubes.

Other analogous methods are those of Snook and Kelly (Brit. Patent 16,853/1913), who adapted the transformer apparatus to this method, so that alternative oppositely directed current impulses operated either tube; the British Thomson-Houston Company (Brit. Patent 6807/1915), Rodriquez (Brit. Patent 135,540/1918), and MacDonald (Brit. Patent 212,285/1922), who described a method requiring no shutter device.

One actual method, due to Lievre, used by Messrs. Watsons, is the adoption of two tubes, with each tube alternately excited by means of a


FIG. 390A.—Stereoscopic Viewing Apparatus.

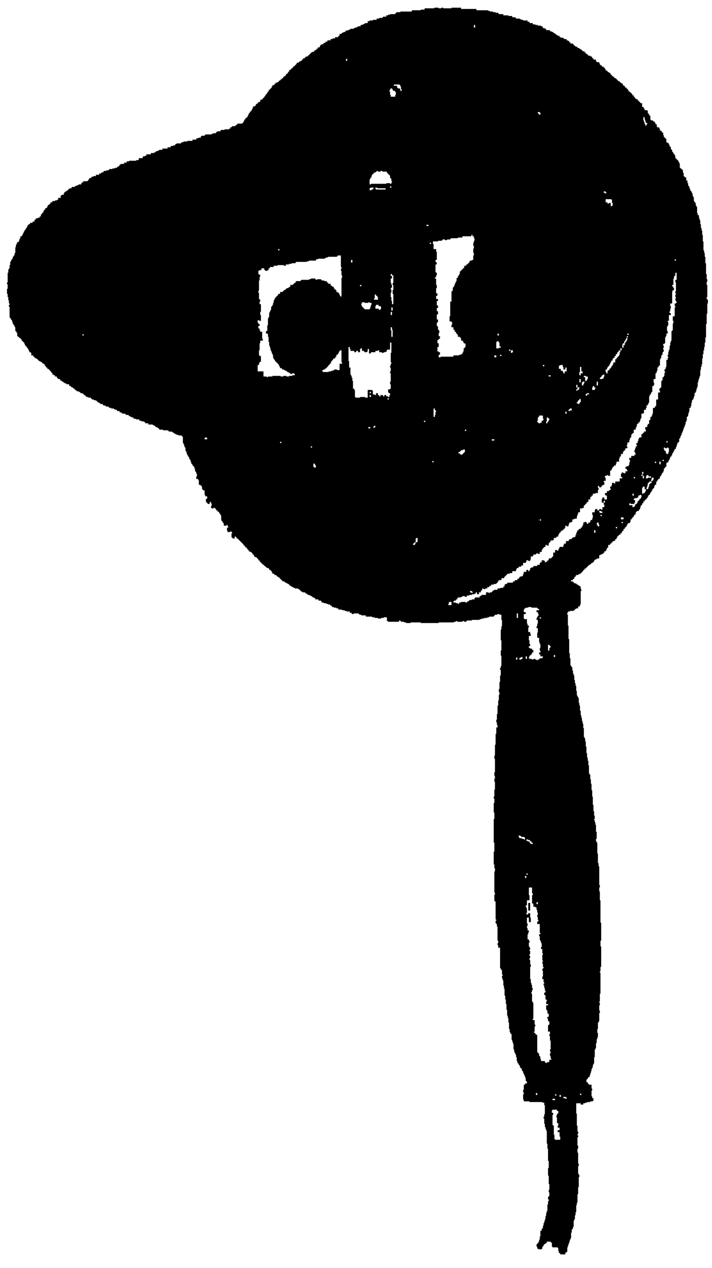


FIG. 390B.—Synchronous Shutter Device.

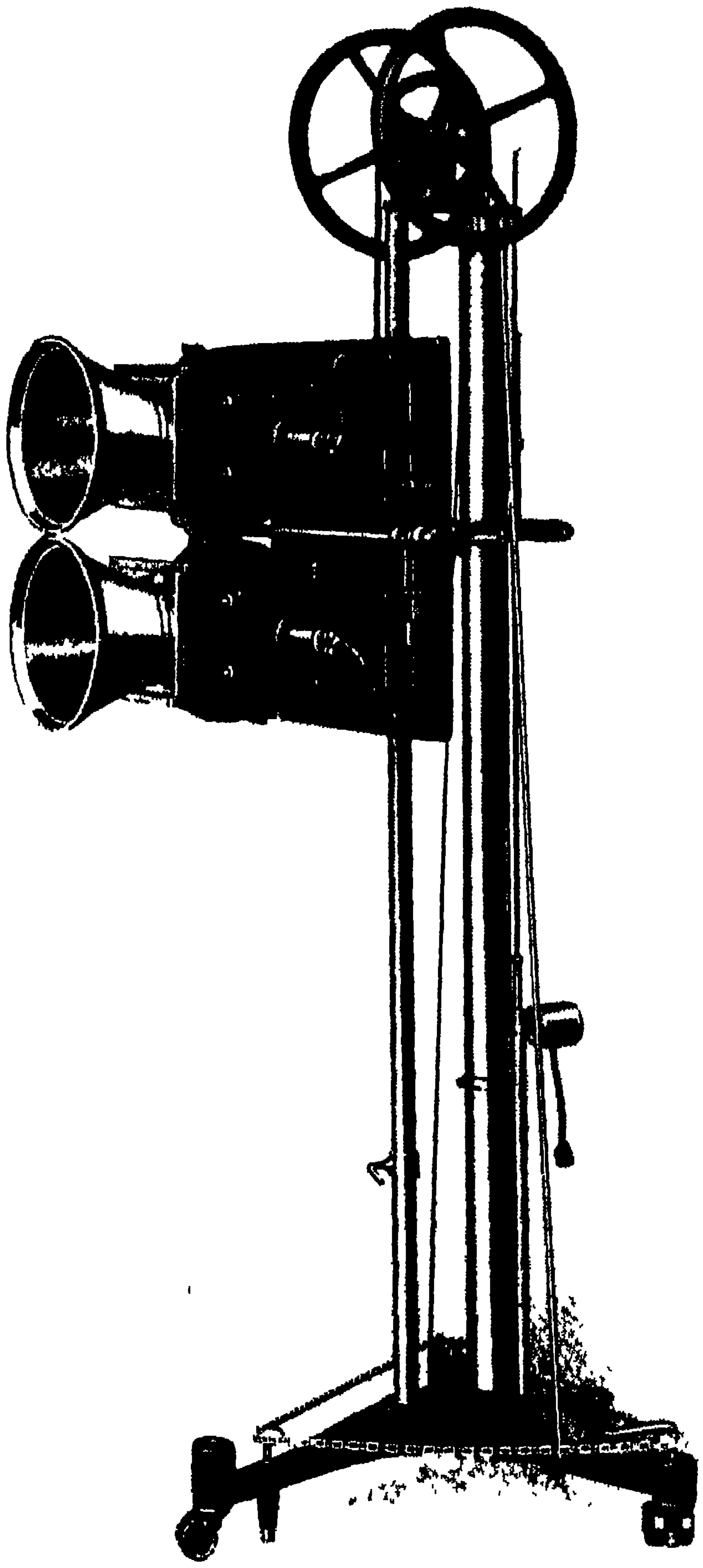


FIG. 391.—Stereoscopic Duplex Tube Stand (Messrs. Keeley-Koett, U.S.A.).

[*To face p.* 421.

driven synchronously by the same shaft S. This is shown in Figs. 394A and 394B, and is essentially a circular diaphragm with a 90° sector K removed, revolving behind a screen H, seen removed in the diaphragm, and so alternatively exposing the tube *viâ* the two holes within the screen.

A stereoscopic arrangement for direct localisation is shown in Fig. 415, p. 430. It should be remarked that some persons appear to have a very strongly developed stereoscopic sense and some to entirely lack this. The latter can often obtain no greater information from a pair of stereoscopic plates than from a single plate which they are able to mentally picture as having depth.

*Hyperstereography.*—This term was introduced to define a particular type of stereographic work in which both the stereoscopic "shift" is greatly increased, as well as the distance between X-ray tube and film.

Stereoscopic relief is essentially dependent upon biocular vision. It has been found in astronomy and aviation that the relief effect is greatly increased if stereoscopic views are taken by a camera, moving along a long

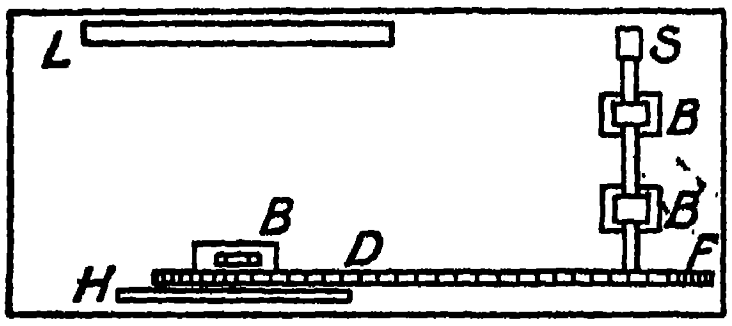



Fig. 394A.—Tyndall and Hill's Apparatus (Shutter Device, Plan).

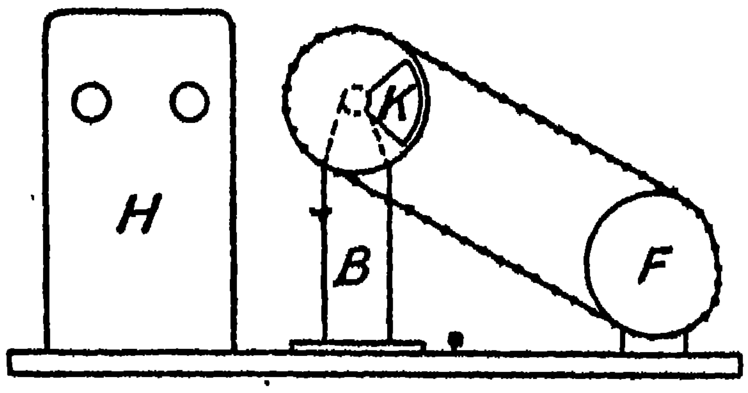



Fig. 394B.—Tyndall and Hill's Apparatus (Shutter Device, Elevation).

displacement line. In order to obtain the same effect in X-ray work, Dioclès decided in 1923 to increase the target-to-film distance to 2·5 metres, but finally adopted a distance of 2·25 metres.

An advantage of this method is that, as in teleradiographic work, distortion is much less and there is better superposition of the film images. At the above distance a square of 10 cm. side is hardly appreciably increased in area of projection, whereas, with the normal target-to-film distance of 30 in. (75 cm.), a square as above is increased in projection to 12·6 cm. per side.

In addition to this advantage Dioclès claims there is an increased sensation of depth. He states that if we look at a statue of given size at 2·5 metres, then we obtain a less sensation of relief than if we regard a replica of one-fifth the size at ½ metre, although in each case the object subtends the same angle at the retina.

It is claimed that if we take two stereographic radiographs with a target shift N times the normal distance between the optical axes (6·3), on examining such radiographs the same sensation is experienced as if the films were of an object N times smaller but N times nearer.

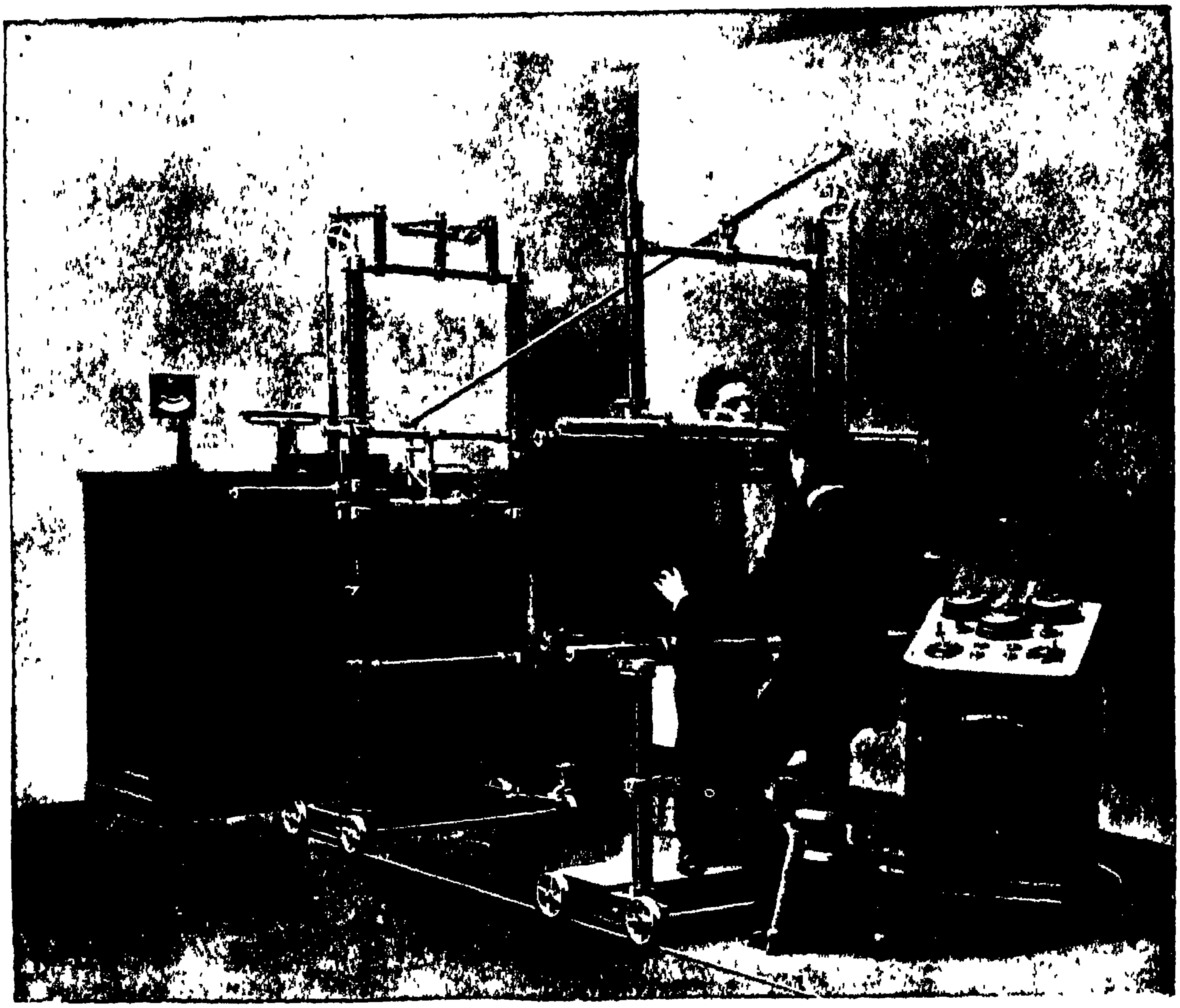


FIG. 395A.—Dioclès Hyperstereographic Apparatus (Gaiffe-Gallot & Pilon).

[To face p. 423.

## CLAMPING DEVICES

The compression devices we have already described in Chapter I Vol. II., mostly also serve at the same time as clamping devices.

To immobilise a patient during radiography and radiotherapy ma forms of clamps have been devised. For holding a patient's body i mobile such clamps are useful, but for limbs, it is rarely that an equa good result, for the brief period of radiography, cannot be obtained by t exertion of a little tact. For therapy, where a long-continued immobil is desired, such apparatus is more useful.

For immobilising limbs very many clamps have been devised, f example, Figs. 396 and 397. In practice a few suitably disposed sandba will give the same result with less fear to the patient when a limb is bei radiographed.

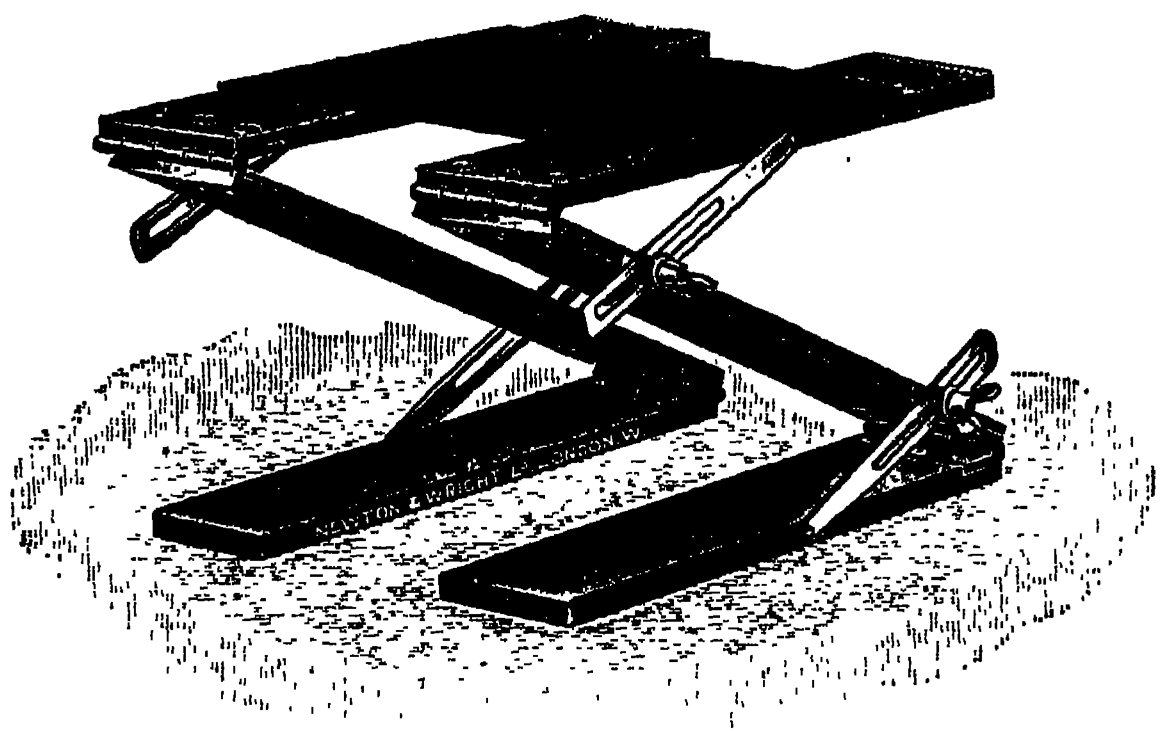


FIG. 401.—Plate Supports.

For finer plates, f example mastoid, ant and teeth, radio graphs, a clamp nearly a necessity, a the exact position very important.

Figs. 398 and 39 show examples of such clamps, the first being designed for sinus and mastoid work and the second for dental work with the clamp and centring device protruding from below the tube holder. The sinus clamp permits any desired adjustment of the head and has a plate tunnel beneath, to facilitate plate changing. A further adjustment permits the rotation of the plate holder to any desired vertical inclination.

Dental chairs have been devised having a clamp in which the head is held still in any one position.

For dental work, where the film has to be within the patient's mouth, it is usual to have some form of film holder which the patient himself holds in any desired position, during the short exposure.

An example of a therapy clamping bridge to immobilise a patient's body during a lengthy treatment is shown in Fig. 400.

Equally important in radiography to the maintenance of position of the patient is the maintenance of position of the plate, which may move in consequence of thoracic or abdominal respiration. Plate holders, such as Fig. 401, which lift the plate just away from the moving body instead of allowing it to rest on the body, are of greatest value in this respect. The

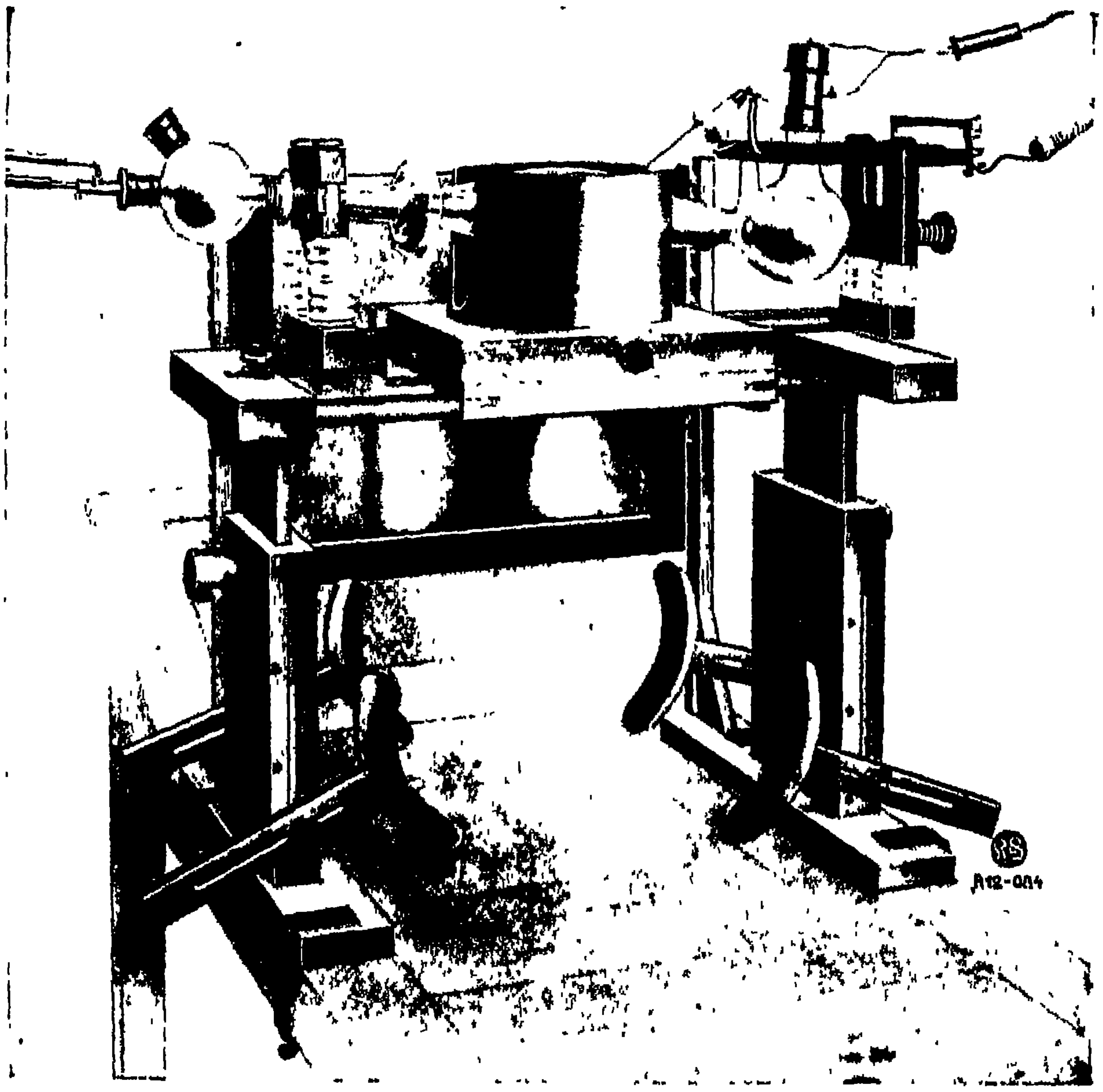



FIG. 400.—Body Clamp for Therapy (Messrs. Koch & Sterzel).

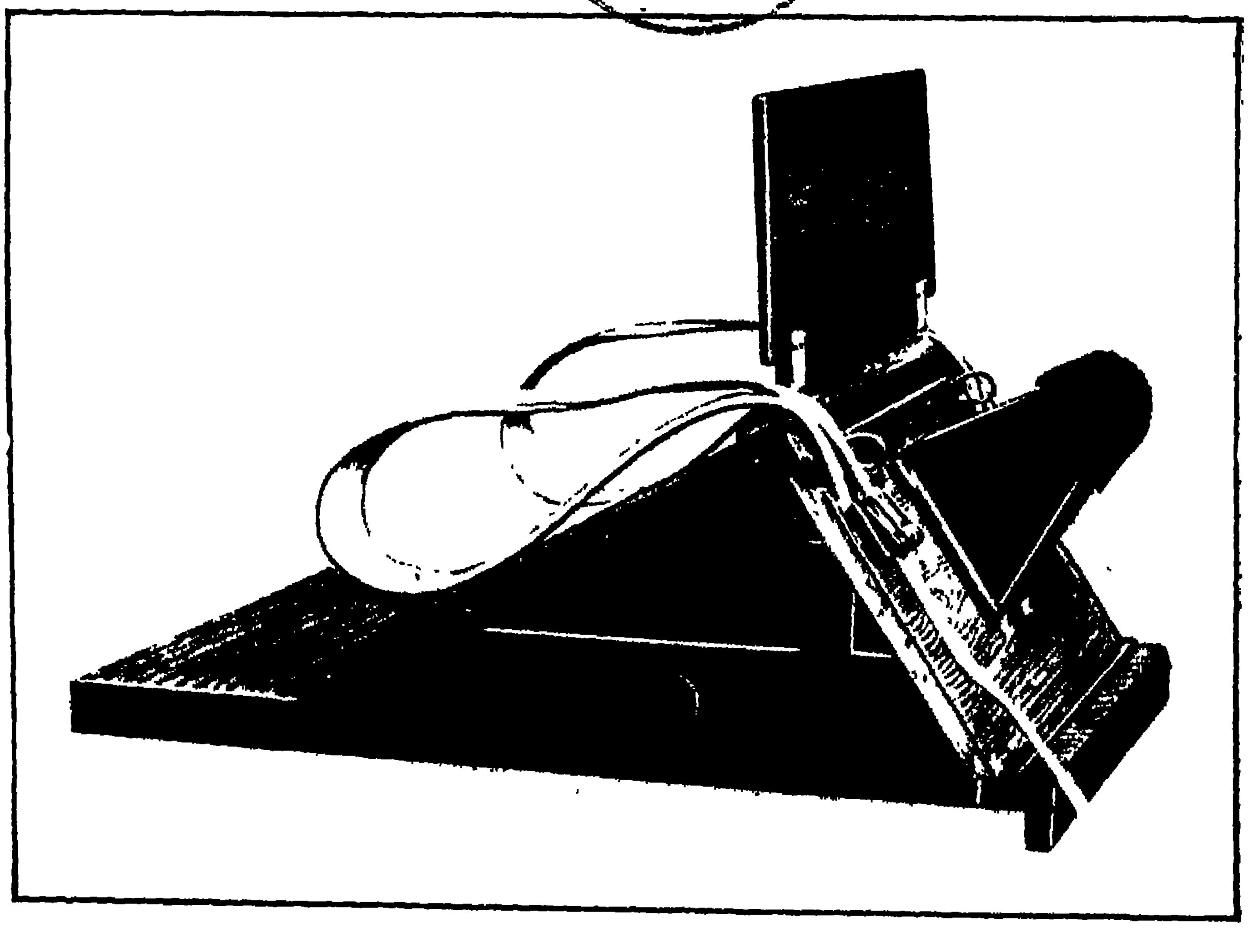


FIG. 402.—Chaoul Duodenal Indirect Viewing Device.

To face p. 425.]

Whilst not used as a routine method, when a nervous and frightened child is being dealt with the instrument is a real boon, and should be an essential accessory of any children's X-ray department.

Similar apparatus is used in France, particularly in military work for the extraction of projectiles. The cryptoscope in this case is strapped around the head. It is very long, and since it must of necessity be of light construction and bad X-ray protection, the length ensures the operator's head is without the field of direct X-radiation. The fluorescent screen is inclined to the vertical plane when the head is in the normal position. To avoid the discomfort of such a long headpiece the apparatus is hinged and, when not in actual use, can be turned back to a more comfortable position, when the accommodation of the eyes is preserved by a window of red glass.

Such cryptoscopes really revert to a method of screening used in the early history of radioscopy * in which the patient was in the light and the observer within a darkened box. This method has undoubted benefits and might advantageously still be used for radioscopy of children and nervous patients.

## ORTHOGRAPHIC APPARATUS

The X-ray shadow, as normally seen upon the fluorescent screen or plate, is, owing to the great obliquity of the radiation, a very distorted shadow. This is partly due to the large area of the tube-box aperture source of radiation giving a large penumbra, but also chiefly due to the large distance between screen and object in relation to the source-to-object distance. Compared to light phenomena, it is a shadow as cast by a candle upon the wall of a room which, even when the object is close to the wall, is well known to be grossly distorted, as contrasted to a sharp shadow cast by a small source of distant light, as sunlight, when the object is similarly near the wall.

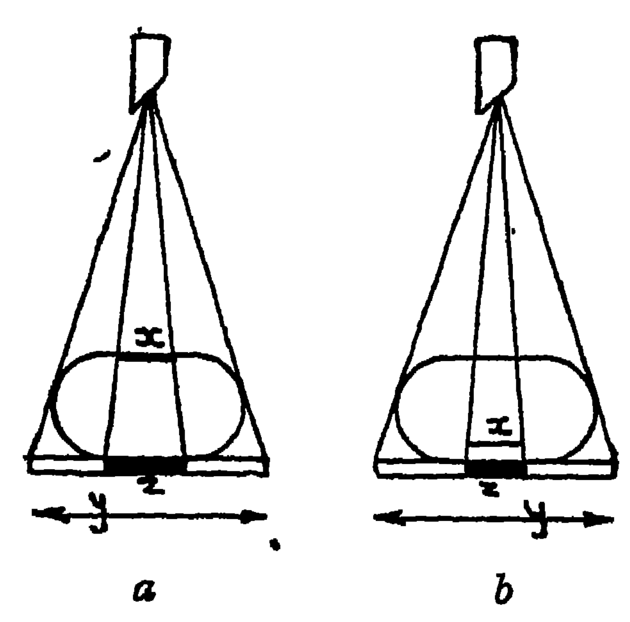


FIG. 403.—Effect of Relative Distance of Body and Plate.

Such distortion may, in radiographs, cause many false appearances—for example, a small separation of an epiphysis may be greatly magnified. It is largely on the correct interpretation of such artificial appearances that the skill of an experienced radiologist depends.

The production of distortion becomes more evident if we consider two situations of a body $x$ (Fig. 403). Then, if $x$ is the true width of the body with respect to the total width of the image $z$, the ratio $\frac{x}{z}$ will differ

* Brit. Patent 25,655/1897.

importance. Given a sufficiently intense X-ray beam, this method is the best, giving an instantaneous picture, and, further, the additional apparatus required is negligible.

On the other hand, if we take a very small source of radiation (Fig. 405), and move the tube to various positions, $T_1$ and $T_2$ to give projections of points, such as *a* and *b*, marking on a suitable fluorescent screen the projections *a'* and *b'*, it follows that we shall so obtain a true projection. This is the near method of orthography.

This method is a slow method, as a sufficient number of points have to be located, gives only a tracing and not an actual plate and requires

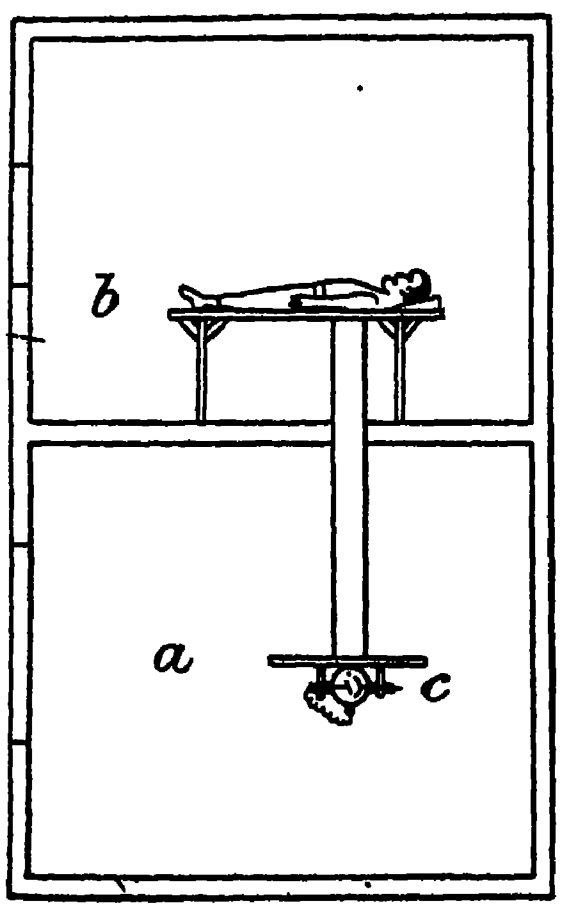



Fig. 408.

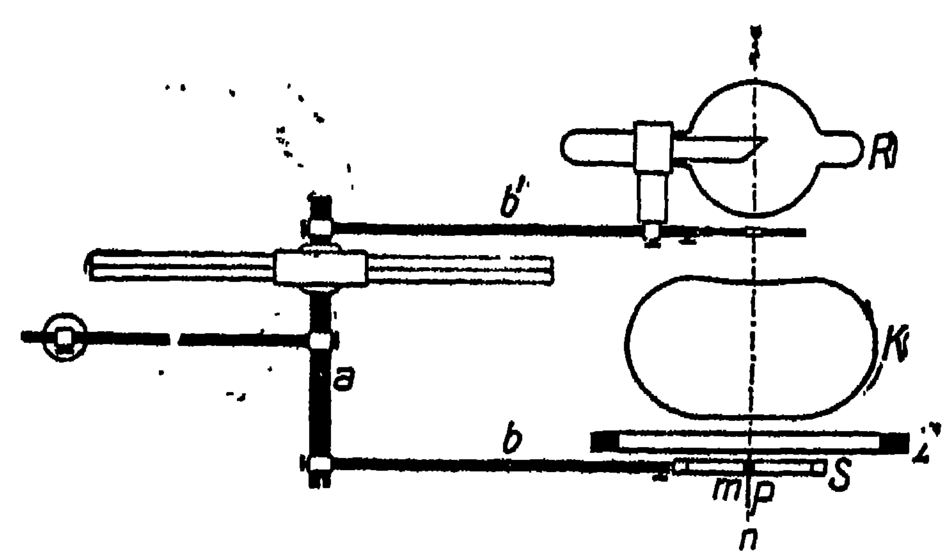



Fig. 409.

more complicated and costly apparatus than the distant method. In view of the time involved the patient is only too liable to move and so cause errors.

An apparatus for the distant method is shown in Fig. 406. It is seen to consist merely of a 3-metre extension carrying the X-ray screen, which has cross wires to allow of accurate centring and has either the glass protection of the screen frosted, or a separate frosted sheet of glass to allow the observer to pencil the practically accurately projected outline.

As shown in the figure, this method is objectionable in that, as the peripheral portion of the X-ray beam surrounds the observer, there is distinct danger, which is however easily overcome by merely supporting the screen within a well-protected lead screen and moving the patient and not the screen to obtain accurate centring of tube, patient and plate.

Fig. 407 shows a similar distant orthographic method in which the tube is at a given distance behind the screen. This is more easily capable of protection since the tube shield has only a small aperture, the radia-

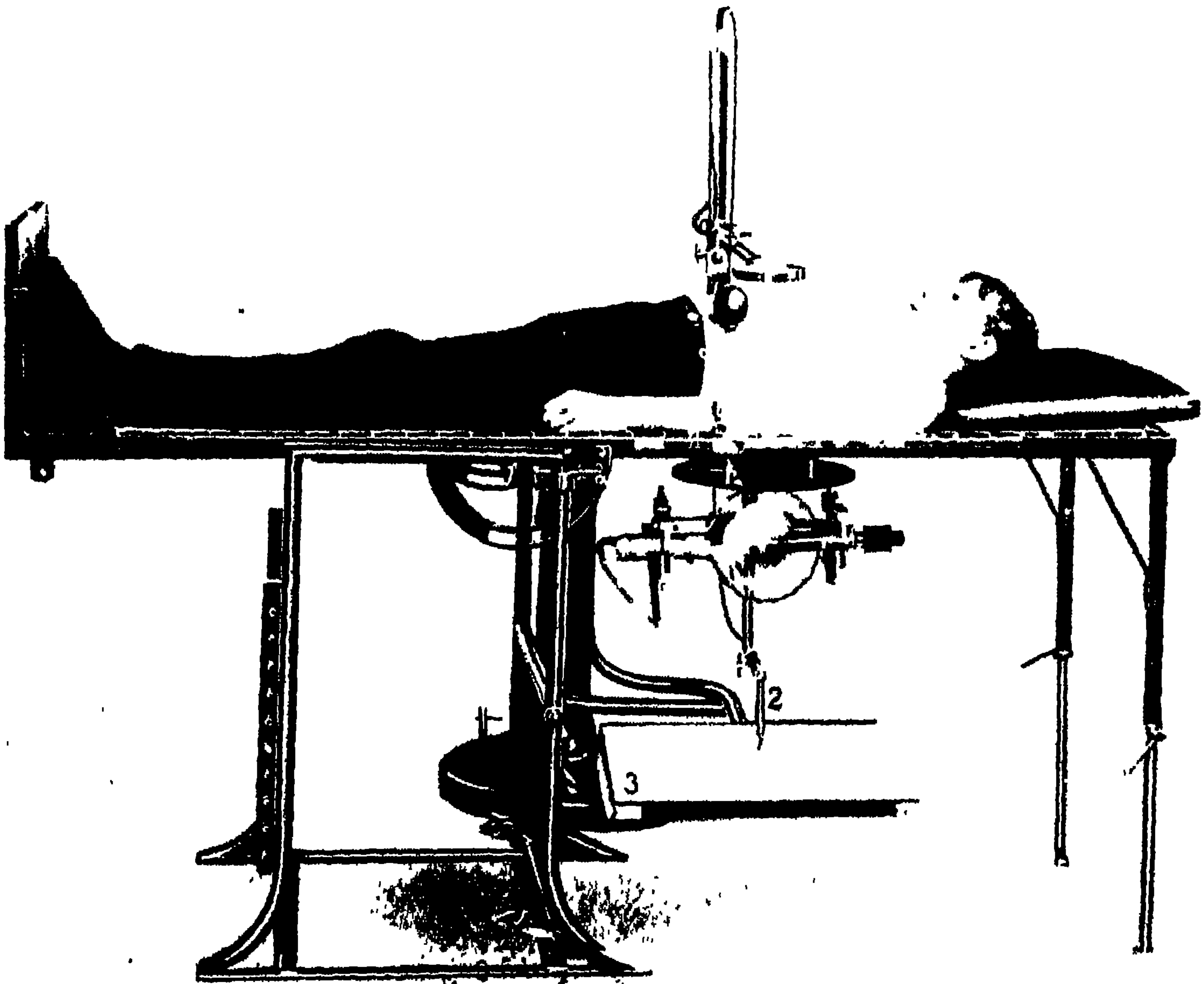



FIG. 410.—Dorn-Groedel Orthographic Apparatus (Couch Position).

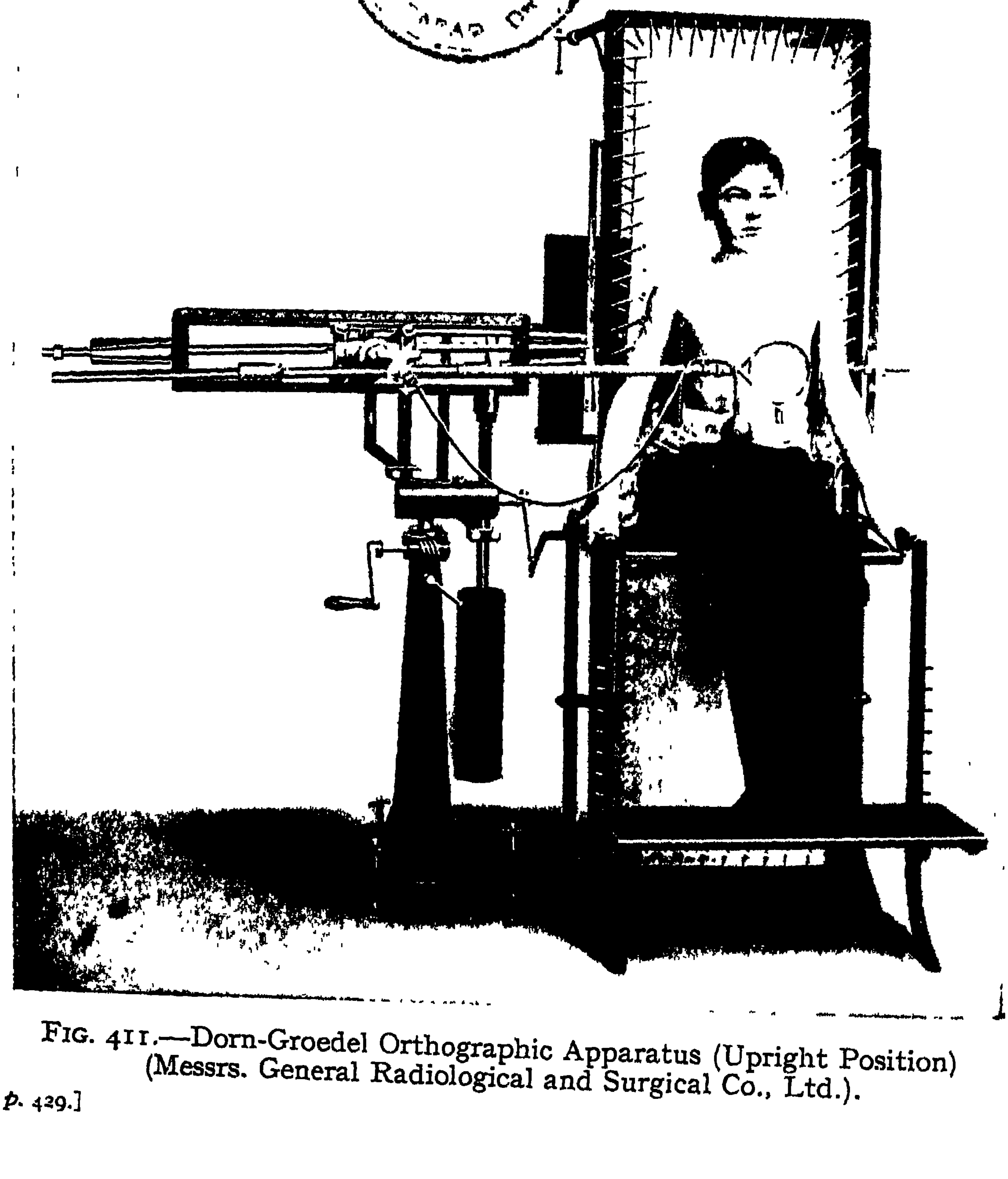


FIG. 411.—Dorn-Groedel Orthographic Apparatus (Upright Position) (Messrs. General Radiological and Surgical Co., Ltd.).

*To face p.* 429.]

*Ortho-stereography*.—From time to time various apparatuses have been produced which have the purpose of reconstructing a three-dimensional image, as in the normal stereograph, and to permit measurements of this image.

If we consider the production of stereographic images on plates $P_1$ and $P_2$ by targets $T_1$ and $T_2$, of an object having a depth AB, then the optical system is as Fig. 413A.

If now we place these plates within a stereographic apparatus so that they are again in the same relative position, and if we view them by our eyes, actually or virtually, at the same positions as the tube targets, then the previous object is reconstructed in space at AB (Fig. 413B).

If now we imagine a vertical wire moving in space, this can be caused to mark first the point A and then the point B, and hence to measure AB.

This process of ortho-stereoscopy has important practical bearings. For example, it is not directly, but only indirectly possible, to measure the anterior-posterior diameter of the female pelvis. If, however, we radiograph this pelvis stereometrically and then reconstruct the pelvis in space by the method above, we are in a position to directly and accurately measure this diameter by means of suitable orthographic apparatus. Similarly, we can measure cranial distances, for example the dimensions of the sella tursica. Of the first to utilise this method was Gillet (Brit. Patent 10,328/1097), whose apparatus is shown in Figs. 414 and 415.

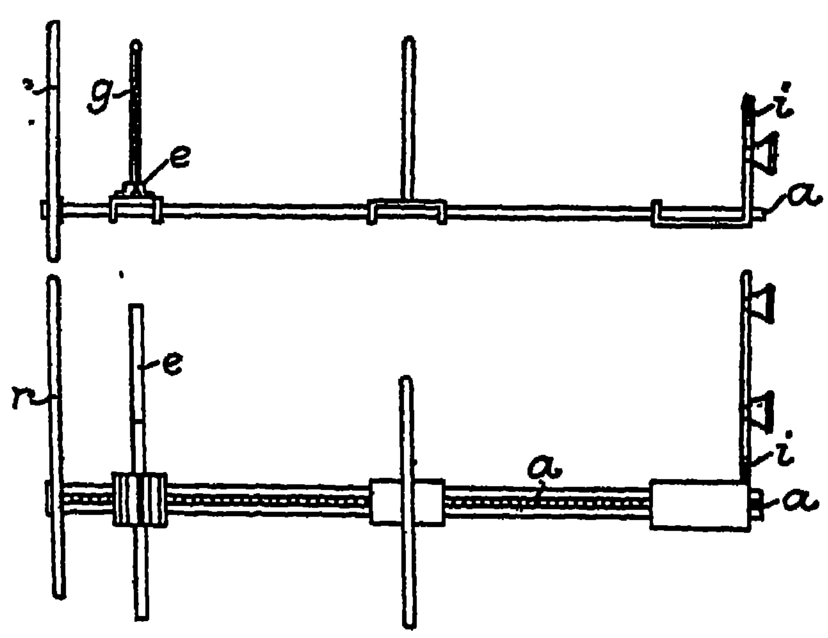



FIG. 415.—Gillet's Apparatus.

In this method a pair of photographs are taken in succession by shifting the tube *viâ* a distance equal to the interocular distance of the observer. The stereographs so produced are then examined in a special stereoscope made to scale. This stereoscope is shown in elevation and in plan in Fig. 415. The eye apertures are made in a screen *i* placed at one end of a graduated bar *a*, at the other end of which the stereographs are mounted on a slide *r*. A sliding frame *e* carries a transversely adjustable vertical wire on which a bead *g* slides. The stereographs being in position, this bead is adjusted in three dimensions until it coincides with the point of intersection of the two lines passing from the eye apertures respectively to the photographic images of the body, the position of which is being determined on the stereographs. The position may also be determined on a reticulated transparent sheet occupying the plane of the frame *e* as shown in the illustration (Fig. 414).

plate-changing tunnel, a stereoscopic movement being simply obtained by means of a scale upon the handle of the cassette.

For stereoscopic work it is an obvious advance on this method to arrange for two plates to be inserted in the plate tunnel so that when either is exposed, the other is protected by a sheet of lead ; the distance between the plates being such that a correct displacement for stereography is obtained. The American manufacturers have devoted much ingenuity to make the exchange of plates entirely automatic, so that a pair of exposures can be taken nearly as rapidly as it is possible to press two separate, but closely located, push buttons.

The exchange of the two plates may be caused by the action of gravity, magnetic attraction, or an air-leak device, as often used in the Potter-Bucky apparatus.

A gravity controlled plate changer is shown in Fig. 417.

Two cassettes are present, and are balanced against each other over pulleys, but the upper one is overbalanced by means of an additional weight. The lower cassette is protected by a thick lead screen. The upper overbalanced plate, ready for exposure, is held by a trigger device. When this is exposed the trigger is released, the heavier plate falls behind the protective screen and, in doing so, draws up the unexposed plate for exposure. The rapid movement is controlled by means of an air-leak device which allows the rapidity of exchange to be controlled by the extent of the leak and, at the same time, prevents vibration of the apparatus, which would occur by a too rapid fall of the upper plate.

This changer is designed for vertical work only. In order to fix the position of the patient and also to allow the apices of the thorax to be obtained (if necessary) the upper edge is recessed.

The stereoscopic shift is simply obtained by the guides along which each plate travels being displaced laterally by the desired distance of 6 cm.

A similar apparatus, adapted for lateral movement of the plates, is shown in Fig. 418. In this plate changer the operating mechanism is entirely an air leak, gravity operation being impossible in the horizontal position.

In both these plate changers the apparatus has to be reset after exposure of both plates, but in some apparatuses this is not necessary, as the plates are shifted by magnetic attraction of solenoids upon iron plate holders, the current to the solenoids being operated by push buttons. In this case each plate is held laterally behind lead shields. Between them is the fluorescent screen. Operation of the correct stops brings each cassette in tu n between patient and screen.

By having the plates rapidly fed into one end and removed at the other end, the apparatus may be utilised for serial photography of more than two exposures.

Serial radiography is of great use when it is designed to obtain a series

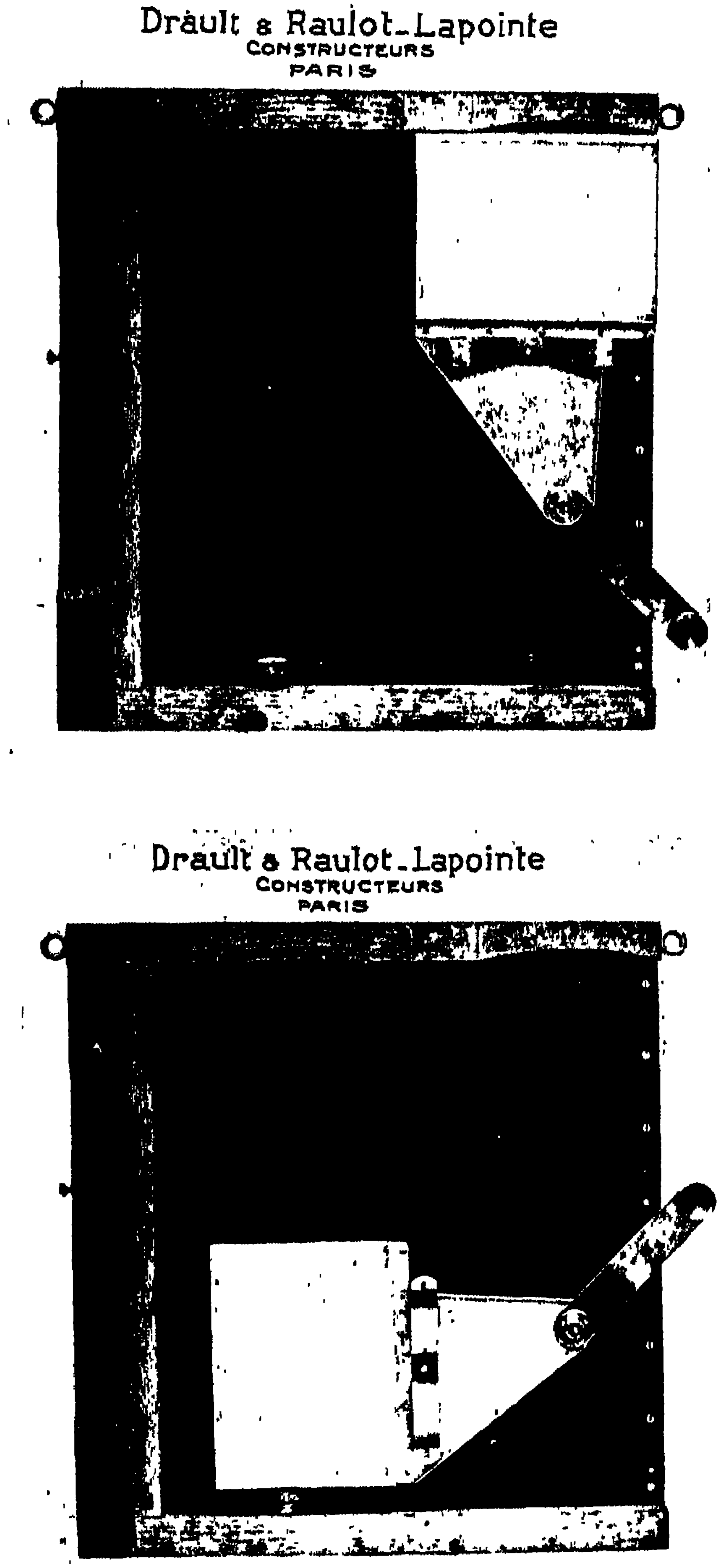



Fig. 419.—Loman Plate Changer.

Gebbert and Schall, which differs from the above apparatus for serial work in ;—

(1) It requires very little space.

(2) It requires only small plates.

( ) It allows intermittent screening; so that before the plates are exposed, the part to be radiographed can be viewed.

(4) It is very simple in operation.

The apparatus, seen in Fig. 421, consists of a fluorescent screen and four plate holders which are carried by a rotating plate behind a heavily protected screen.

By means of handles, seen on either side, the plates can be rapidly brought to cover the unprotected opening, shown in the figure with a fluorescent screen. The size of plates and screen is 9 × 12 cm. The plate changer is made to rotate about the vertical plane of the holder and is adjustable in height.

The fluorescent screen may be viewed by reflected light, by means of the mirror seen below the actual plate changer.

A built-in plate-changing apparatus for a screening stand is shown in Fig. 422. A fluorescent screen A is between the two cassettes B protected by lead. Either cassette can be very simply and quickly brought behind the screen by pulling the cords D and C below.

Most plate-changing apparatus is cumbersome and in consequence slow to operate. Messrs. X-Rays, Ltd. have overcome this by a very simple but effective device known as the " Seriascope " (Fig. 423). This is actually an X-ray roll film camera, having an outer case lined completely with lead except where exposure occurs. Inside is a roll of double-coated film upon spools, and passing between fluorescent screens. It can be equally applied to a couch or a screening stand. The film is caused to move by turning a handle to the right through 180 degrees, and as the movement is brought about by such a simple operation it is claimed six exposures can be made in 10 to 15 seconds.

The objection to the method appears to be the necessity of exchanging the protected fluorescent screen for the Seriascope before the instrument can be used, which necessitates the loss of some time, during which the X-ray screen appearances may have changed. It does not however appear impossible to arrange for the instrument to be rapidly slid behind the screen in a specially constructed apparatus, in which case there would be undoubted merits in this method

## X-RAY CINEMATOGRAPHY

As is well known, the normal cinematograph is a rapid succession of separate photographs. For these to blend into a continuous visual

mental stage and is unlikely to be realised until the X-ray tube is still further improved.

A partial cinematographic method is of value in the study of the heart's movements. In this method the transverse width of the heart at various levels is shown by radiography *vid* a narrow slit upon a moving film. Such movements are found to agree with the electro-cardiograph curve.

The method was first used by Reider and Rosenthal in 1912, later by Crane in America, in 1916, and more recently by Cohn and Stewart,* in England by Knox † (1925), and still more recently (1926) by Stenstrom and Westermarkt. ‡ Knox was able to obtain slit exposures as high as twenty-five per second, and, like Rieder and Rosenthal, show the relationship of the heart's systole and diastole to the electrocardiograph curve.

## LOCALISATION

Localisation by X-rays is of chief importance in military surgery. In civil practice it has its chief application in casualty work, *i.e.*, in the localisation of fragments of broken needles, foreign bodies due to explosions, etc.

To aid localisation work numerous apparatuses, usually expensive, have been evolved, and, in normal practice, these may be entirely dispensed with. All we require is a simple knowledge of elementary geometry. The majority of localisation apparatuses are merely methods of avoiding these few simple calculations by means of cumbersome and expensive apparatus, which only has a useful application when a large number of localisations have to be rapidly done, as routine work. Such apparatuses then have useful application since :—

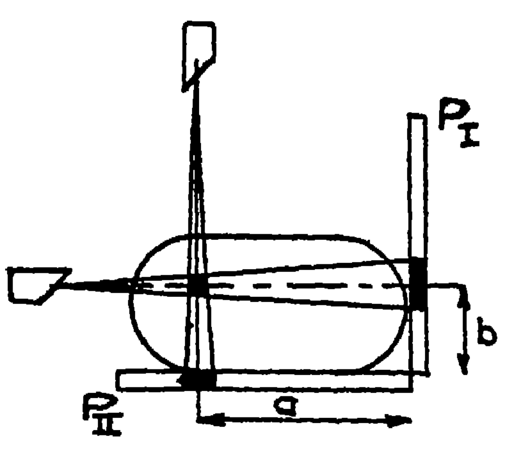


Fig. 424.

(1) They increase the speed at which localisations can be carried out.

(2) They eliminate errors of calculation.

The normal radiograph is a projection image pure and simple, and errors may arise as regards the relative position of, say, a foreign body due to ;—

(1) Rotation of the patient's body from the position perpendicular to the normal ray (Fig. 404, *a*).

(2) Rotation of the plate from the position perpendicular to the X-ray beam (Fig. 404, *b*).

(3) Incorrect centring of the body within the central rays of the X-ray beam emitted from the tube target (Fig, 404, *c*).

* *Trans. Assoc. Amer. Phys.*, 39, p. 197 (1924).
† *Brit. Journ. Rad.*, 21, p. 142 (1925).
‡ *Acta. Rad.*, 5, p. 408 (1926).

The above method suffers from disadvantages ;

(1) Either the tube has to be rotated through the vertical plane by 90 degrees and errors occur unless a specially accurate tube stand is used, or ;

(2) The patient has to be rotated *viâ* 90 degrees to obtain anterior-posterior and lateral views. This is still more difficult to perform accurately than the first method, even when lead guides are used, for example, placed upon the sternum and spine, etc.

When a limb is the subject of localisation this objection is not so great, as the limb is capable of easy rotation. Moreover four marks may be utilised by the method, which is obvious from Fig. 426, in which absolute perpendicularity of AB and CD is not necessary.

A modification of this method, due to Shenton, is to screen the limb with a small portable screen and, having determined the position A (Fig. 426),


Fig. 429.—Illustrating the Tube Shift Method.

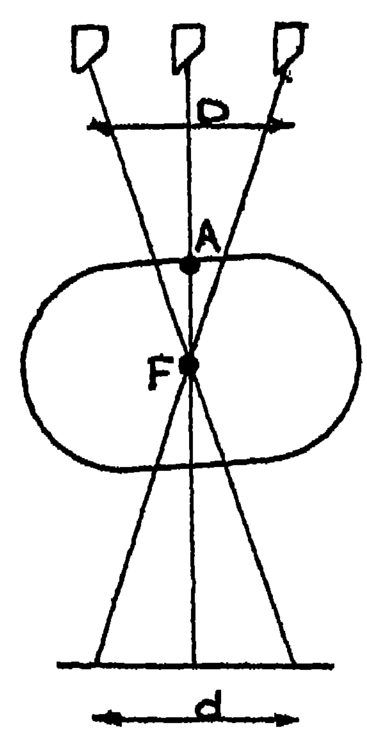



Fig. 430.

to mark this with a lead mark. The limb is then rotated 90 degrees and a small lead slider is adjusted along the length of a marker, until this is above the boundary of the limb, when the foreign body and its lead mark are below the centre of the screen, as shown by cross wires. It is then obvious that, the limb being in its former position, if the surgeon cuts directly downwards from the point A, to a depth as given by *d* upon the slider, he will be accurately upon the foreign body, or, if this is small, very near to it.

A very similar method is that of Gamlim (Fig. 428), who employs a small fluorescent screen protected by lead glass and with metallic cross wires. The depth *d* is measured by means of a sliding aluminium pointer moved along the axis of the screen handle, by means of a sliding knob and

than any formula, it being a matter of regret to find radiologists blindly using some formula for localisation, and apparently quite unaware this is so simply derived, that it is not worthy of memorising. The distance $h$ we have obtained is the height of the foreign body above the plate, and $x$, the distance of the foreign body below A, which is more useful, directly follows by subtraction of $h$ from the total body height at A, Fig. 430.

The source of error in this method is due to the difficulty of accurately measuring $d$, when this is small. Any such error of measurement is multiplied by the value of H, which is large and so increases the error.

For very great accuracy $d$ should therefore be measured by a micrometer or vernier gauge.

It is of course in this method equally possible to use two separate plates with the vertical position of A marked. Whilst two such plates can be used to obtain a stereoscopic view, this is not to be recommended, as small errors may be introduced during plate changing.

The photographic plate can be equally substituted by the fluorescent screen, the position of the shadow being marked with each tube shift upon a suitable frosted screen glass surface.

From Fig. 432 it is obvious that if we have the tube accurately centred upon the foreign body, it is only necessary to employ one tube shift position, since we then still have a ratio $\frac{D}{d} = \frac{H - h}{h}$.

The objection to this simple method which still requires two half exposures, is that the distance $d$ is now still smaller and the relative error of its measurement is liable to be still greater. This may be compensated for by increasing the tube shift D.

Methods of refinement have been introduced into this method for repetition work, by having the distance H always accurately fixed by the apparatus.

Since $d$ is then directly proportional to H, a screen, having a calibrated scale, can be used, which directly reads values of D or indirectly the value of $h$, so much simplifying the method. A still more accurate method due to Holland is to use a small fluorescent screen, with suitable protection, in which the tube is first centred so that a lead mark at A covers the foreign body. The tube is then moved 10 cm. and the foreign body is now located at B, the distance AB being accurately read by means of a vernier. This scale is calibrated directly or indirectly in terms of the distance $d$, so that the depth is immediately read from the scale or calibration curves, which may be drawn up for various screen-to-target distances.

Another method of localisation is to mount two parallel cross wires above the diaphragm of the undercouch tube box, but not connected with it, the distance $d$ between which is very accurately known.

The tube box is centred upon the foreign body and, by screening, this

whence $X - h$, the distance of the foreign body below the fluorescent screen, is determined.

In all such methods as those described it will be noticed that great error results if the tube is not accurately centred within the tube holder. Various methods of carrying this out are possible and have been described in Chapter VII, Vol. II., namely ;—

(1) By cross wires upon the tube-box aperture.

(2) By means of a simple tube, which may be directly placed over the tube box, so restricting the beam to a thin pencil, *i.e.*, giving an orthographic arrangement (Fig. 434) ;

(3) By cross wires upon a centralising apparatus due to Gillet ;

(4) By means of a pendulum with a lead bob which, to damp rapidly its oscillation, is within an oil container ;

(5) By means of a correctly fixed opaque projection from the tube box which corresponds to the central spot when a given tube is correctly inserted in the tube box ;

A very convenient method of determining the focal centre of a tube is by means of Burrell's cylinder (Fig. 435). This is a short wide cylinder of lead which, if radiographed, gives a shadow which is of truncated triangular form. If the sides of this shadow are extended their point of intersection determines the focal centre, as is obvious from the illustration.

To avoid calculations in localising work, an apparatus (Fig. 436) has been introduced by Mackenzie-Davidson, in which the geometrical construction of Fig. 431 is reconstructed.

To use this apparatus it is necessary to first know ;—

(1) Distance H, *i.e.*, anticathode to plate distance ;

(2) Distance D, *i.e.*, movement of the tube.

The developed X-ray plate is then placed upon the cross wires of a horizontal glass plate and the position of one image is marked by means of a pointed lead weight, known as a " mouse," owing to its shape.

A second " mouse " is then placed at the second image and the actual geometrical ray paths are reconstructed by taking threads to the cross arm above, the height of which represents the plate-to-anticathode distance and the cross-arm distances, the distance of the tube shift. The intersection of the crossed threads, measured by an engineer's pointer level, then gives the distance of the foreign body from the plate.

For any given value of plate-to-anticathode distance, the horizontal limb can be maintained in one position and only the tube-shift length varied.

This apparatus is of great use in warfare, where rapid and repeated localisations have to be carried out. The actual localisation is however already carried out before this apparatus comes into use, and this is merely a method of reconstructing the geometrical localising arrangement

introduce error, is to be preferred, and is certainly cheapest and for a single case quicker.

Shenton has produced a screen localiser shown in Fig. 438, in which any convenient shift of the foreign body obtained by moving the tube from the central position is indicated by movement of a pointer to which is mechanically geared a second pointer, so that the distance of the second pointer from the central position is always double the distance of the first pointer. The screen is placed in contact with the skin of the patient and the tube and screen are adjusted until the shadow of the foreign body appears in the central position. A convenient shift of the foreign body shadow having been produced by moving the tube, the pointers are adjusted until the first pointer touches any convenient part of the foreign body shadow. The screen is now raised in a vertical direction until the second pointer touches the corresponding part of the foreign body shadow, *i.e.*, the distance moved by the foreign body shadow from the central position is doubled by merely moving the screen vertically upwards. The distance moved by the screen will be the exact distance of the foreign body from the surface of the screen in its initial position and the depth of the foreign body from the skin of the patient is directly read off from the vertical scale of the instrument.

This instrument serves to illustrate one of the innumerable ingenious localising apparatuses which arose during the course of the late War.

A perusal of the patent literature and the radiological journals of all countries during this conflict shows innumerable localising devices, the description of which would entail a separate book.

Many of these devices were independently originated in various countries and so bear varying names—for example, the Mackenzie-Davidson apparatus is known as the Marion-Darion apparatus in France; others are characterised by their intricacy rather than any particular merit.

In France a well known and used localising instrument is the Hirtz Compass. This instrument consists of three horizontal arms each at 120 degrees to each other and each carrying three perpendicular feet at their extremities upon which the instrument rests. A fourth director leg can be moved along an arc so that its lower point always coincides with the centre of the base formed by the three feet. The method consists of taking two radiographs with a tube shift whilst the positions of the compass feet were indicated by lead balls. The compass is then arranged upon the plate and the direction of the fourth director leg adjusted to point to the image of the foreign body. The sterilised compass could then be transferred to the patient and the director arm then points towards the foreign body and so aids its surgical removal. Still more complicated methods of use of this compass will be found in French radiological literature. Analogous compasses have been utilised by Luzoir, Debierne, Massiot, Grandgerard, etc.

Ironside Bruce has done much work in this connection, and his method is extremely simple. He employs a normal undercouch X-ray table, but the upright standard is capable of carrying a small accessory arm, shown in Fig. 439. This upright is fitted with a small radioscopic screen which can be rapidly removed or swung out of position and replaced by a director holder of exactly equal length and capable of sterilisation. To allow the arm carrying the screen to be quickly removed the cross arm is pivoted and rotates upwards. The procedure is then as follows ;

Usually the approximate position of the body is known from a previous localisation. The surgeon fixes the limb in the most convenient position for his own purpose, sterilises the limb, etc.

The surgical field being covered by a sterile towel, the radiologist now adjusts his screen and, the tube-box diaphragm being cut down as finely as possible, he locates the foreign body and moves the tube box so that this is exactly at the point of intersection of the cross wires with which the screen is accurately fitted. The tube box and its upright standard then being locked into position, he removes his screen. The surgeon now inserts the sterile director support, removes the sterile towel, and presses the director directly downwards until he either impinges upon the foreign body or considers he has penetrated sufficiently deep. He then loosens the clamp of the director needle, and the carrier is swung away, and if necessary, the surgical field being again covered with a towel, the relative position of needle and foreign body can be checked by the radiologist again mounting the fluoroscopic screen.

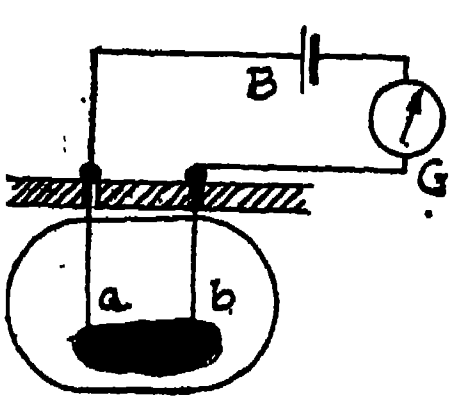


FIG. 440.

This being exact, the surgeon then follows the needle until the foreign body is exposed.

This method is very efficient, except for very small bodies such as needles, where it is quite possible for the surgeon to pass along the side of the needle sought for. In this case two director needles may be inserted at right angles to each other and their position of intersection sought *viâ* one route.

The director has in some cases been duplicated by two needles (Fig. 440), each of which is insulated from the other. These are then pressed towards the foreign body (known to be metal) and, when contact is made by both needles, an electrical circuit is completed and a bell or lamp indicator is so operated.

The procedure in this case is by no means simple, but, with careful selection upon anatomical grounds, the insertion of the needles is very often preferable to a large open wound, in which the needle may be undiscovered owing to its having been passed.

Surgical operations have been very often carried out entirely by X-radiation illumination. There are very serious objections to this practice, namely ;—

provided beneath the head rest, one half of which is lead protected, so that a single plate serves, by reversal, for both the necessary exposures.

The whole apparatus is placed upon a suitable couch and acts as a pillow for the patient's head. The essential localising apparatus (Figs 442A and 442B) is on a separate stand and consists of an upright with an horizontal arm $C^5$ capable of adjustment, as regards height, by a clamping screw $C^4$.

This horizontal arm supports a lead cone E and a lead ball D. The latter is so adjusted that it presses upon the eyelid of the eye under examination. This pressure compensates so that the ball actually extends into the orbit, to a distance equal to the thickness of the eyelid, *i.e.*, it is at

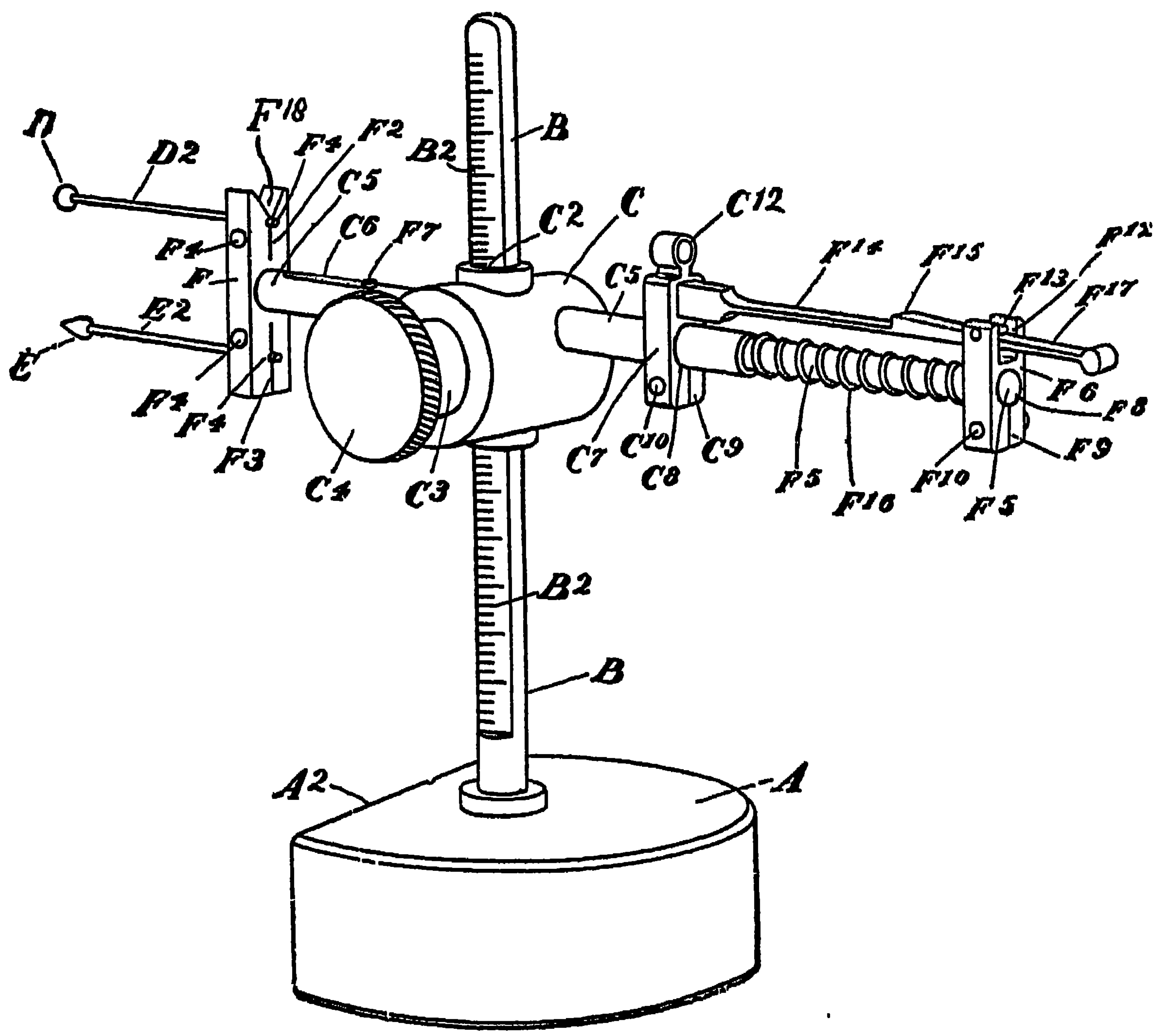



FIG. 442B.

such a distance as would be necessary for it to just touch the cornea, if the eyelid were not interposed. This ball is accurately adjusted to the centre of the cornea by means of the sights $F^{18}$, $C^{12}$ and $F^{13}$, the central position being subsequently maintained by instructing the patient to look along these sights at an object about 4 ft. away.

When this ball is accurately adjusted the trigger $F^{17}$ releases a spring $F^{16}$ which causes the ball-and-cone support to fly back a distance of 10 mm. The distance between ball and cone centres is 15 mm. The procedure of taking plates is then as follows ;—

An overhead tube is used with a small aperture and central ray

point of intersection $F^2$ with the line projected from the side view will be the position of the foreign body, as viewed from the front. Hence the position of the foreign body is located in horizontal and vertical planes.

Whilst this is the usual description given to this method of localisation

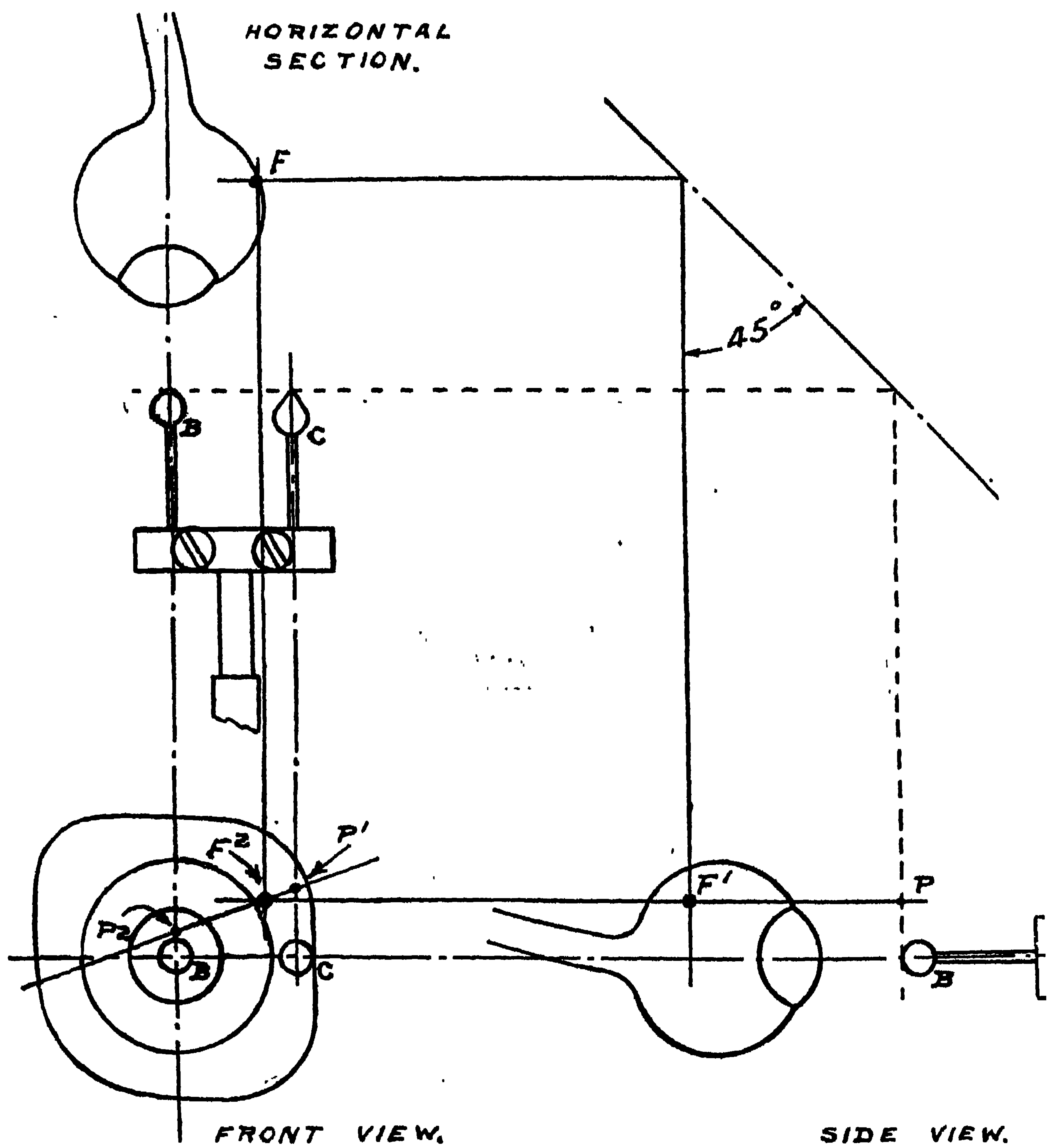



FIG. 446.—Sweet's Localisation Chart.

we can more briefly summarise the matter by saying, the second plat gives us the unknown projection $d'$ of the distance of 15 mm. between bal and cone. The distance from the central axis of the foreign body in th vertical plane is $b$, where $a + b = 15$ mm., whence, by measuring the rati $\frac{a'}{b'}$, the ratio $\frac{a}{b}$ is determined, and hence $a$ and $b$. The depth of the foreig

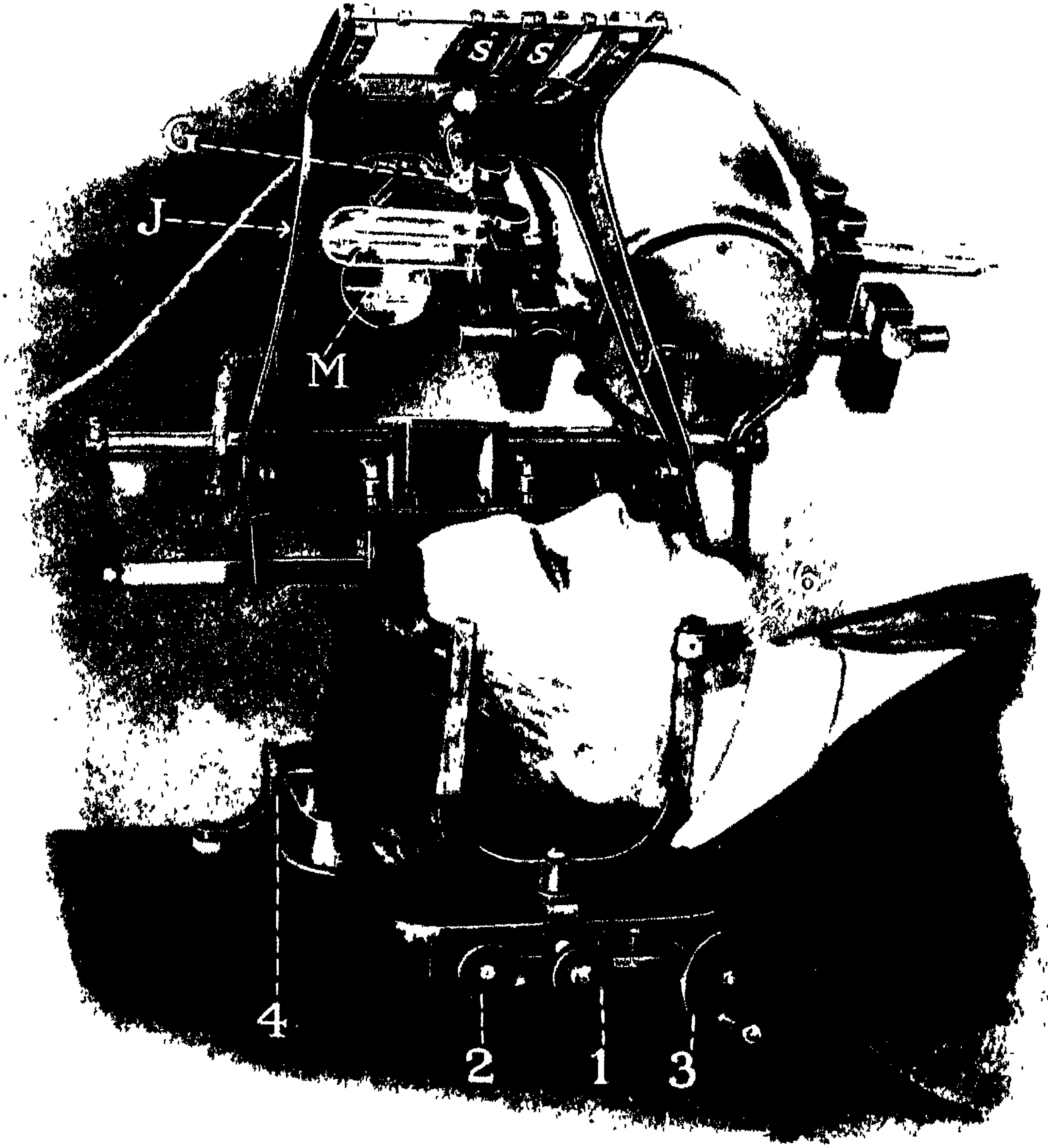



FIG. 447.—Later Model of Sweet's Localiser.

[To face p. 451.

lid, or some other suitable location on the skull, and the distance of this wire is accurately measured from the centre of the cornea. The patient now sits with his injured eye nearest the plate holder and, looking at a distant horizontal point to keep the eye parallel to the plates, two plates are exposed with the usual stereoscopic shift of 3 cm. from the mean position.

This differs in no way from the usual method of localisation and is usually worked out by the Mackenzie-Davidson localiser in the ordinary manner, the cross wires giving the distances of the foreign body from the side of the face touching the plate holder in two planes, and the shadow of the lead wire upon the eyelid, allowing the distance of the foreign body below and behind the wire to be determined.

This method is inferior to the Sweet method, since the distance between the shadows of the foreign body is small in relation to the plate-target distance and, even with careful measurements, great relative errors can arise. Further experimental errors may arise if the Mackenzie-Davidson instrument is used instead of direct calculation.

*Skull Localisation.*—This offers no special features except that, to aid subsequent description of the location of the foreign body, it is usual to map out the skull with lead wires which so appear on the plates during radiography.

These wires are usually placed as follows ;—

(1) One wire passes vertically over the skull from each external auditory meatus.

(2) One wire from the nasion to the external occipital protuberance.

(3) Lateral wires from the nasion to the external auditory meatus.

(4) Lateral wires from the external auditory meatus to the external occipital protuberance.

These are shown in Fig. 449, but other regional landmarks will be obvious, both for the skull and in other regions of the body.

Foreign bodies in the skull are usually relatively large (bullets). Whilst accuracy is desirable, it should be always remembered that, during the usual surgical interference in the skull, it is usual to expose a very large area of the brain rather than a small trephine hole.

The methods of localisation are in no way different to those described. True anterior-posterior and lateral views are most convenient. As with other methods of tube shift, the cross-thread localiser may be used if desired.

We may conclude this section by drawing attention to the radiation dangers of localisation work, where the tendency is to use localising screens of small area which, until the tube diaphragm is shut down, radiates a much greater area than the protected screen. In addition the natural desire to use skilfully the hands may result in their being unprotected, as when demonstrating some point to the surgeon. There is so a natural

(14) Describe an apparatus for (*a*) distant orthography, (*b*) near orthography, and discuss their relative advantages.

(15) Describe a plate-changing apparatus.

(16) Discuss the present limitations of X-ray cinematography.

(17) How would you accurately locate a small piece of metal embedded in the eye ?

locally supported provincial hospitals to be often superior to the larger London hospitals.

Not least important in the final result will be the radiologist's own business acumen and his knowledge in estimating the probable cost, not only of radiological apparatus, but of building operations, joinery, etc.

The radiologist is well advised not to patronise one single apparatus maker, but, for all major additions, to obtain competitive tenders from at least all the English apparatus makers and then to form his own opinion entirely apart from any persuasion or statements of these companies' travellers and agents.

In this connection, for the larger hospitals, it is a good economic proposition to employ permanently a first-class electrical instrument apparatus mechanic, whose salary will be more than recovered if he is able, as should be the case, to construct apparatus to the requirements of the hospital's radiologists. Such a mechanic is of more importance than a physicist, whose only duty is to carry out work, which the medical radiologist can very easily learn to do, with a better insight as to the medical requirements.

Failing such a mechanic, the radiologist will often find that a little tactful conversation will enlist the hospital engineer to his service for less pretentious manufacture of apparatus and, if he is a capable all-round engineer, his services will be invaluable.

All installations will be modelled upon the best installations, after which it is a matter of commonsense to follow these principles for smaller installations. There is no reason why they should not be proportionally followed in installations in private practice, *i.e.*, it is as equally important to protect one's next-door neighbours from X-radiation as to protect the patients of a hospital in an adjoining building.

Where the amount of work required does not warrant the installation of a special department and the appointment of a radiologist, a hospital will be best advised to make arrangements with some larger local hospital, or some private radiologist, rather than to instal the type of apparatus usually advertised by " you turn the handle, we do the rest." Such an apparatus, left to the non-radiological trained, ever-changing house surgeon or house physician, will not give satisfaction and will always be eventually more costly. It should always be remembered that the business of a radiologist is not the mere production of X-ray plates but diagnosis, and an incorrect diagnosis by an unskilled person is more dangerous to the patient than a clinical diagnosis made on clinical grounds only.

It must always be remembered that, to diagnose an obvious fractured femur, or obvious advanced phthisis, an X-ray plate is unnecessary. It is only in the cases of questionable fracture, or questionable phthisis, etc., that an X-ray plate becomes of its greatest value. The finer shades of

relegated to him. We do not propose to discuss a general electro-medical department, but only the radiological department. In general other forms of treatment can be usually fitted into a well-designed radiological department, for example, a waiting-room or physicians' room will serve the same purpose, whatever the varied forms of treatment given.

In the writer's opinion the requirements usually advisable for a complete radiological department are :—

(1) A radiographic and radioscopic room
(2) One or more radiotherapeutic rooms.
(3) Waiting-room for patients.
(4) Dressing-room for patients.
(5) Developing or dark room.
(6) Plate-storage room.
(7) Accommodation for medical staff.

THE HOUSING OF AN X-RAY DEPARTMENT

| Cottage Hospital. | Hospital up to 60 Beds. | Hospital up to 200 Beds. | Large General Hospital. | Large Hospital with Teaching School. |
|---|---|---|---|---|
| | X-ray treatment (ordinary) (100) | X-ray treatment (ordinary) (200) | X-ray treatment (ordinary) (400) | X-ray treatment (ordinary) (400)<br>X-ray treatment (intensive) (400) |
| X-ray room (200) | | | Radiographic room (250) | Radiographic room (ordinary (250)<br>Radiographic room (special) for screening (200) |
| | | Radiographic room (200) | | Screening-room ordinary (350) |
| | Radiographic room (200) | | Screening-room (350) | Screening-room (for serial plates, etc.) (170)<br>Demonstration room (600) |
| | | | Medical Officers' room (130) | Medical Officers' room (200)<br>Examining-room (120) |
| | | | Office (130) | Office (180)<br>Nurses' room (sewing, etc.) (180)<br>Plate viewing-room (130) |
| | | Office (130) | | |
| | | | Plate-store room (130) | Plate-store room (180)<br>Service room (100)<br>Laboratory (200) |
| Dark room (80) | Dark room (100)<br>Waiting-room<br>Lavatories | Dark room (100)<br>Waiting-room<br>Lavatories | Dark rooms (250)<br>Lavatories<br>Waiting-room<br>Workshop (150) | Dark rooms (350)<br>Waiting-room<br>Lavatories<br>Workshop (150) |

*N.B.*—The figures in brackets indicate the approximate floor space in superficial feet.

building is already existent the walls may be rendered with at least 1 in. of this cement on each side.

This is therefore the cheapest protective material which can be obtained. The surface of this wall can be rendered with Keen's or other cement and painted. Lorey recommends a limewash which will absorb any nitric oxides and acid fumes evolved by the apparatus. This is most economical, but the author has employed with success unglazed (egg-shell) tiles. These are most hygienic and would readily allow the X-ray room to be treated as an operating theatre as regards sterilisation for operations such as localisation and extraction of foreign bodies. The prime cost is however very expensive (about 35*s.* to 40*s.* per square yard laid), but is recovered by there being no subsequent re-decorating costs.

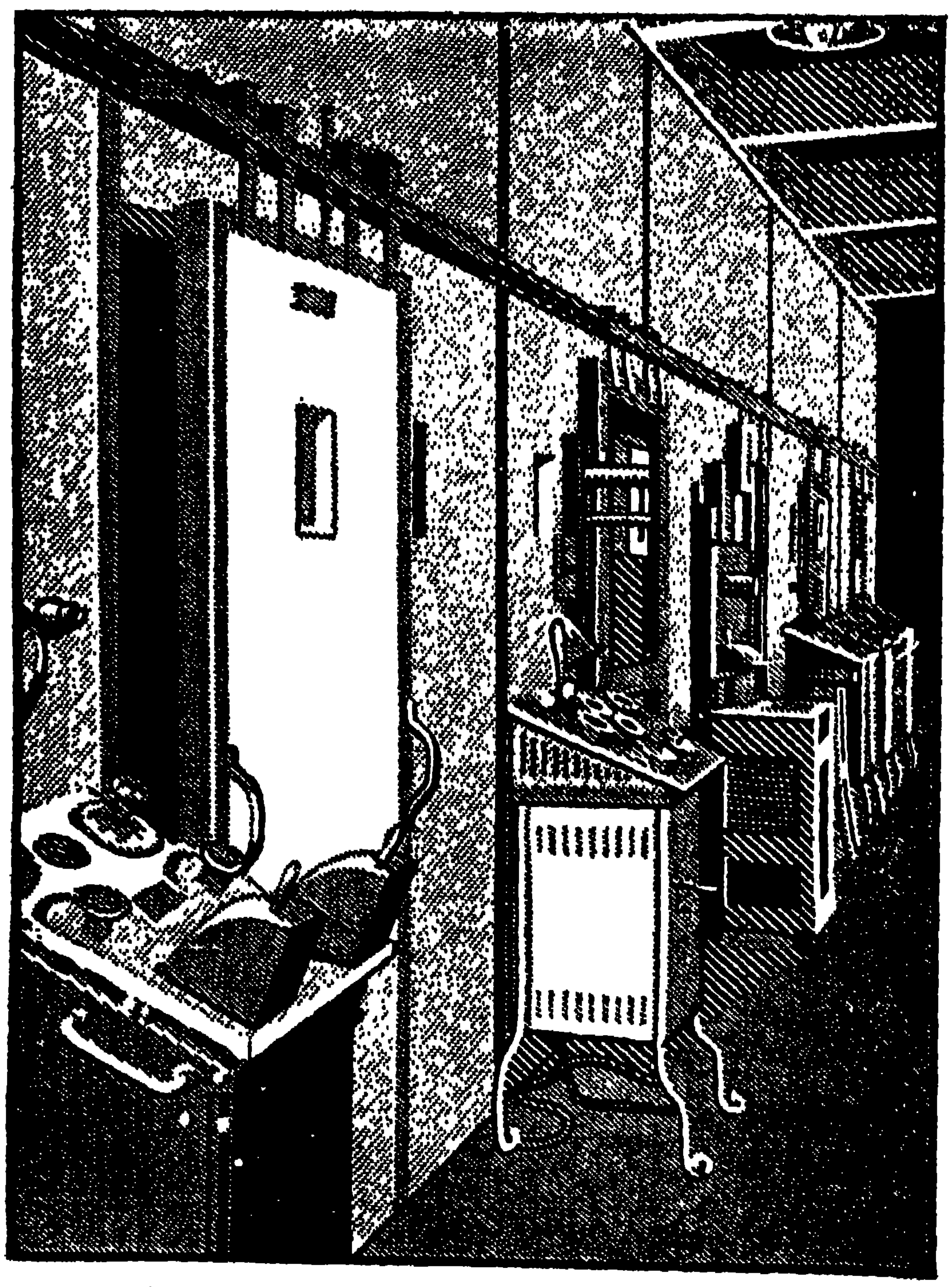


FIG. 450.—Barium Cement Sliding Door (C. H. F. Müller).

The colour should certainly not be a dead black, as in the older X-ray installations, but, the window coverings being efficient, a mediumly light colour, such as a rose-pink or a green, is most useful and less depressing to both the operators and patients than a black colour, although egg-shell black tiles can be obtained and may be used for the dark room.

*Doors.*—The difficulty with barium protection is the protection of the doors.

Various alternatives are possible, namely ;—

(1) Barium cement may be built up within a steel frame, and the sliding door so formed is mounted upon rollers as in Fig. 450. A sliding door and not a hinged door is preferable, as this prevents jarring of the cement. The objection to such a door is that it is heavy and is most applicable to treatment rooms rather than radiographic rooms, where persons are continually passing in and out.

(1) Wooden folding shutters S can be used (Fig. 453). This method is however cumbersome if the windows are large and high. These fold back in sections and the last section may form the outer cover of a recess in which the folding sections fit when the window is opened to light. All edges must overlap. These shutters are cumbersome, liable to jam, and are not recommended.

(2) Sliding shutters overlapping at the edge (Fig. 454). These are still more cumbersome as, unless hung on rollers, they are nearly sure to jam. For such shutters, three-ply wood is admirable.

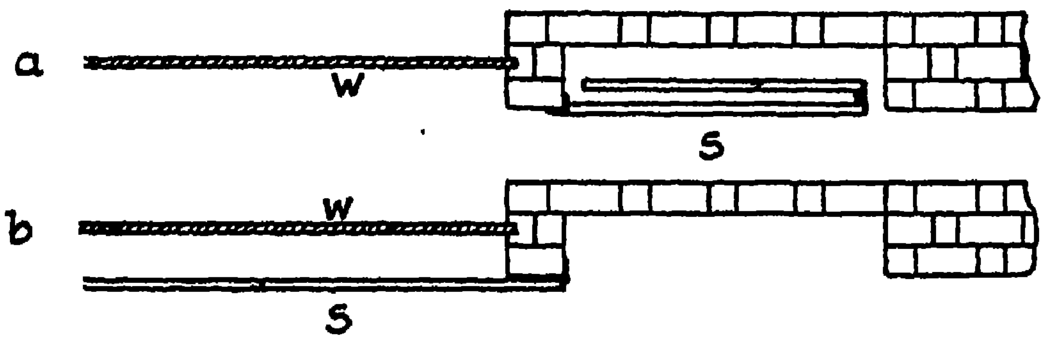



FIG. 453.—Folding Shutters.

(3) Roller blinds. The type of blind used for shop fronts may be used. These are extremely light-tight, but are somewhat expensive. They require a box corresponding to the fascia of a shop front into which they roll when the window is uncovered. This is very apt to collect dust but, if easily obtained, such a blind is to be desired.

(4) A roller blind of stout black fabric. These require little space, are cheap and easily worked. They must however, to avoid light creeping round the edges, overlap the window by several inches and fit into a frame. An example is shown in Fig. 455. They may be either worked by a winch as shown, but practically, a spring roller, with mere pulling down and fastening will be found to be as useful. They will last for many years with reasonably careful usage.

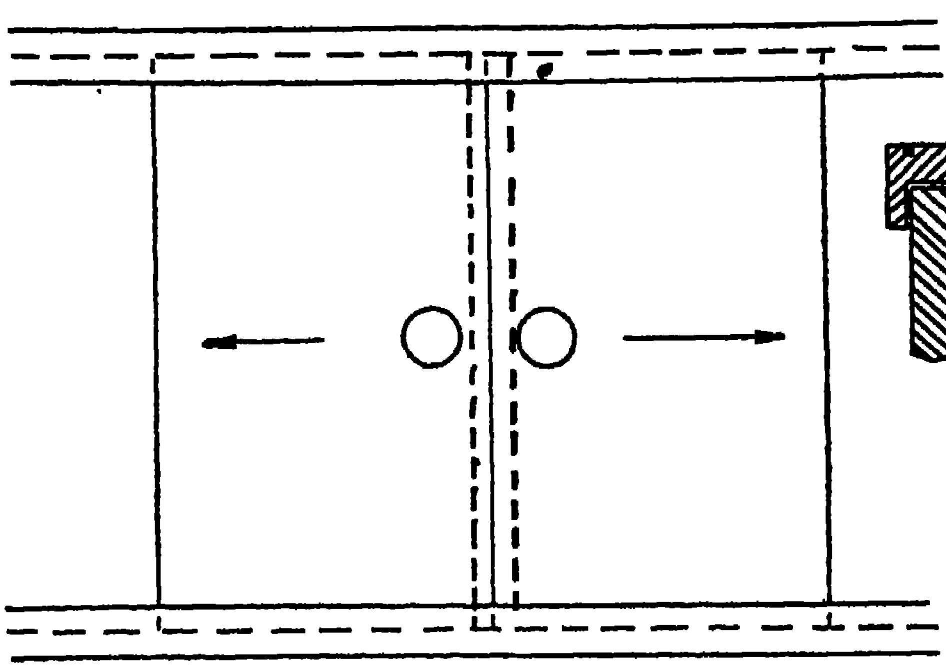


FIG. 454.—Sliding Shutters.

*Floor.*—For the floor of radiographic rooms we have various alternatives. The floor should certainly be non-conductive, as this minimises the occasional electrical shocks which even an experienced radiologist will from time to time receive. For this reason ordinary concrete is not recommended.

We have for selection ;—

(1) Wood.

(2) Rubber.

(3) Cork.

(4) Composition.

A wooden floor, and particularly parquet, is the cheapest, but has as

*Heating.*—A fire, or gas fire, in consequence of the light emitted, is not permissible. We have a choice of non-luminous electric heaters, or steam with central heating. The selection will largely depend upon circumstances, electric heaters being preferable to dust-collecting steam pipes, which, to avoid cramping of the aerial arrangements of the high-tension leads, should be arranged around the floors and not as is often the case around the ceilings.

*Lighting.*—Electric lighting is imperative. The necessary number of points, for good illumination when the room is not in X-ray use, should be installed and governed by one or more switches where necessary. One or more red or green lights, separately operated, for use during screening to avoid interference with the operator's visual accommodation should be installed. These should be brought to a junction box with plug connections, to allow connection to a foot switch, if desired.

All modern lighting is of the metallic tubular type to comply with fire insurance companies' regulations. The indirect system of lighting in which the light is reflected from the ceiling only is very suitable. The lights used during the intervals between screen examinations are invariably red or green. The latter is said to be more restful and equally non-photographically active for greater illumination. The decision between either colour is largely a matter of choice. The writer has used both and, with the latter light, it is certainly surprising how one may read small print in the X-ray dark room by this light, whilst the plates are entirely unaffected.

Rodgers * has utilised for lighting the X-ray room strip lamps concealed in the cornice of the room, which are gradually dimmed by a resistance, and replaced by a violet light, which is again dimmed to total darkness, in order to avoid plunging nervous patients from full light to darkness.

During screen examinations all the control instruments upon the switch table are conveniently illuminated by a weak red lamp.

The only other control instrument is the milliamperemeter which, owing to its being in the high-tension circuit, has to be placed in the aerial system at a distance.

To illuminate this a small neon (or other inert gas) lamp (Fig. 456) may be placed in circuit. This will illuminate when current is flowing *viâ* the aerial system, but has a negligible energy consumption.

Such a lamp, which is in direct circuit with the milliameter, may be short circuited and put out of use when desired. Its advantage is that it allows the control of the current during screening, and therefore absence of danger of over-loading the X-ray tube, without the necessity of spoiling the visual accommodation by turning on a normal light which, if small, must be closely situated to the milliameter and would be in risk of direct sparking between the meter and low-tension lamp circuit.

* *Brit. Journ. Rad.*, 21, p. 124 (1925).

They are supported by insulators of at least 1 ft. depth and preferably 18 in. The insulators which are seen in Fig. 482, are easily constructed by any mechanic, at about one-quarter of the cost charged by an X-ray company.

They may be of glass, porcelain, ebonite, paxolin, or similar insulating material. Glass and porcelain are used upon the Continent, but in England ebonite is chiefly used.

The objection to ebonite is that it so easily warps, particularly in sunlight, and the insulator legs, at all angles to the ceiling, are then very unsightly. Paxolin does not suffer from this disadvantage and is much used in America (Fig. 458).

To avoid fracture of the brittle insulating material each insulator leg should carry a screwed metallic end having a hole just greater than the diameter of the aerial tubing for the insertion of the latter.

This aerial gear will consist of the two distinct leads for gas-tube work and three leads for electron-tube work. Even when, in consequence of expense, electron tubes are not to be used, the radiologist installing a new department is well advised to instal three leads to avoid future expense.

A suitable distance apart of these leads, in a moderate-sized room, is 18 in. between the two high-tension leads and a distance of 6 in., between one of the above leads and the third lead for the tube filament. This latter is far more than necessitated by the voltage, but allows the connections to be very easily made. Occasionally the return filament third lead is a flexible lead within one tubular lead.

These should be arranged around the room, the outer lead being at least 1 ft., and better 18 in., from the wall. The author favours this method as allowing the apparatus to be installed around the room, leaving a free central floor space. It is, of course, equally possible to arrange the leads to run down the centre of the ceiling or, in a long room, to arrange the leads to run parallel to the back wall and from these "bus-bars" take off perpendicular connections where desired.

A well-designed form of tubular aerials of American origin is shown in Fig. 458.

Connections to the apparatus will be made by means of spring "rheophores" (Fig. 459). The old-fashioned metal-tape rheophore, giving continuous brush discharge from the sharp edges, is extinct. These rheophores should be of stout flexible conductor and preferably rubber insulated, to avoid partially a heavy shock by accidental contact in the dark.

To facilitate their placing in position, they should be carried upon an insulating handle of sufficient length to easily reach the aerial tubes. With electron tubes one rheophore may conveniently be double. The connections are maintained by flat springs which press upon the tubes.

The constant placing and removal of such rheophores continually jars

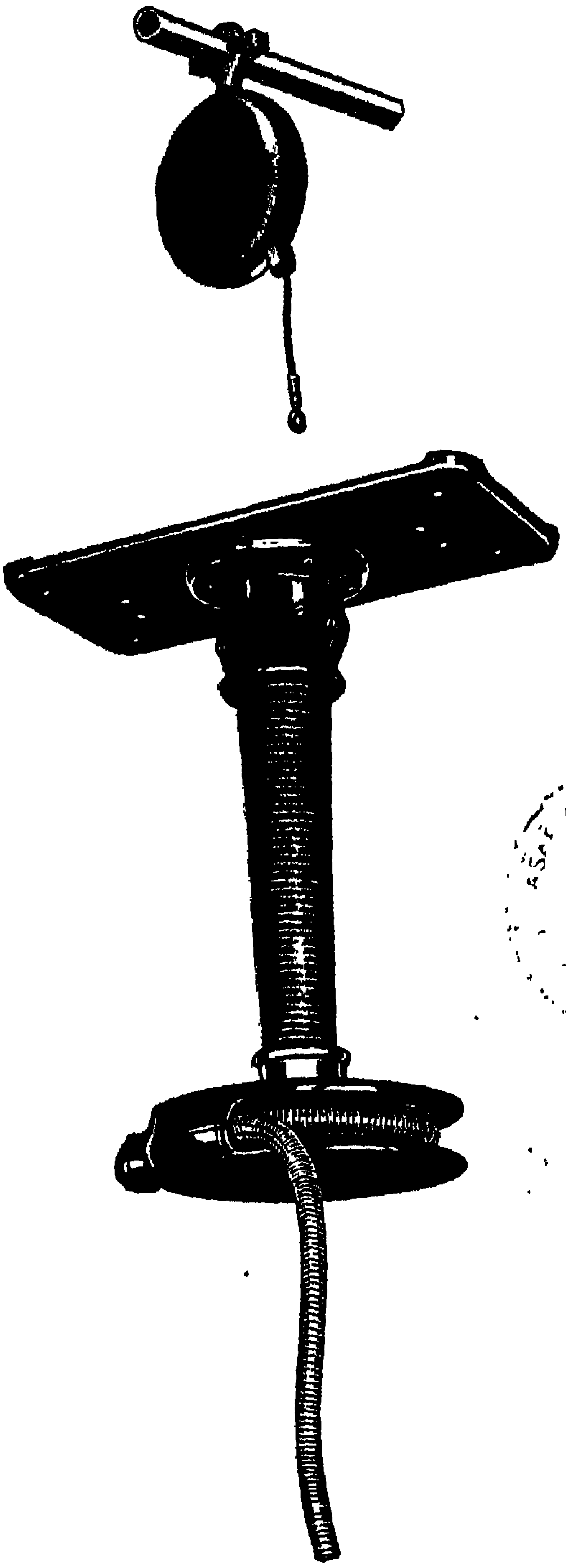


FIG. 459.—Rheophores.

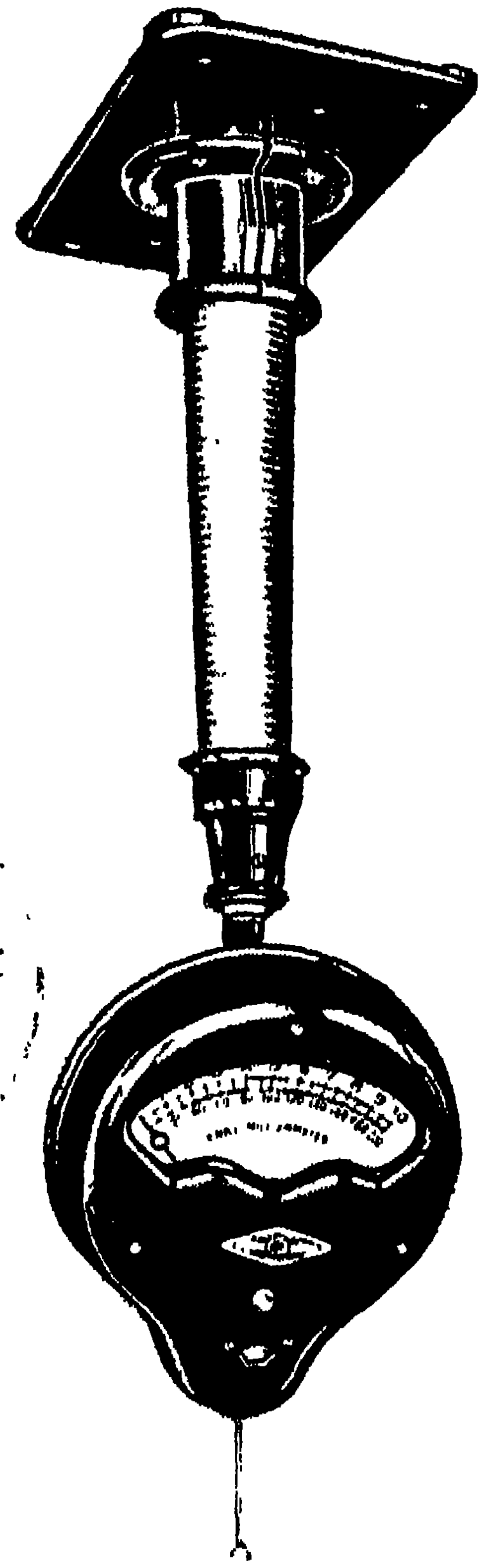


FIG. 463.—Aerial Ammeter (Messrs. Acme International Co., U.S.A.).

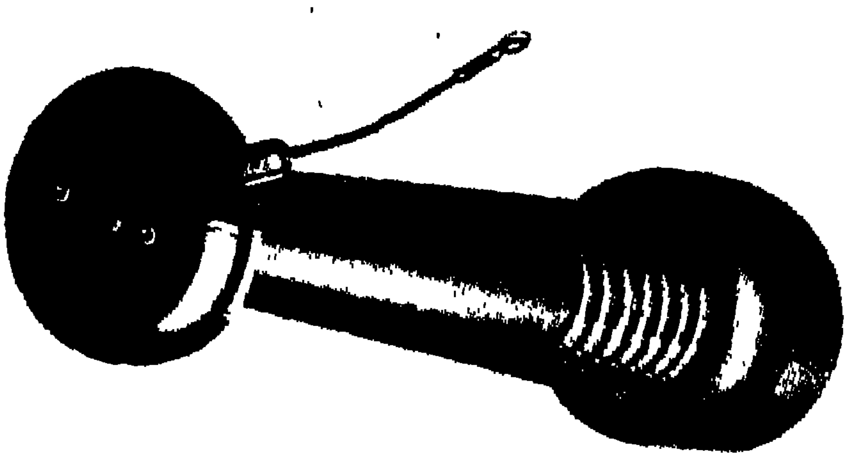


FIG. 468.—Wall Bushing (Messrs. Keeley-Koett, U.S.A.).

*To face p.* 467.]

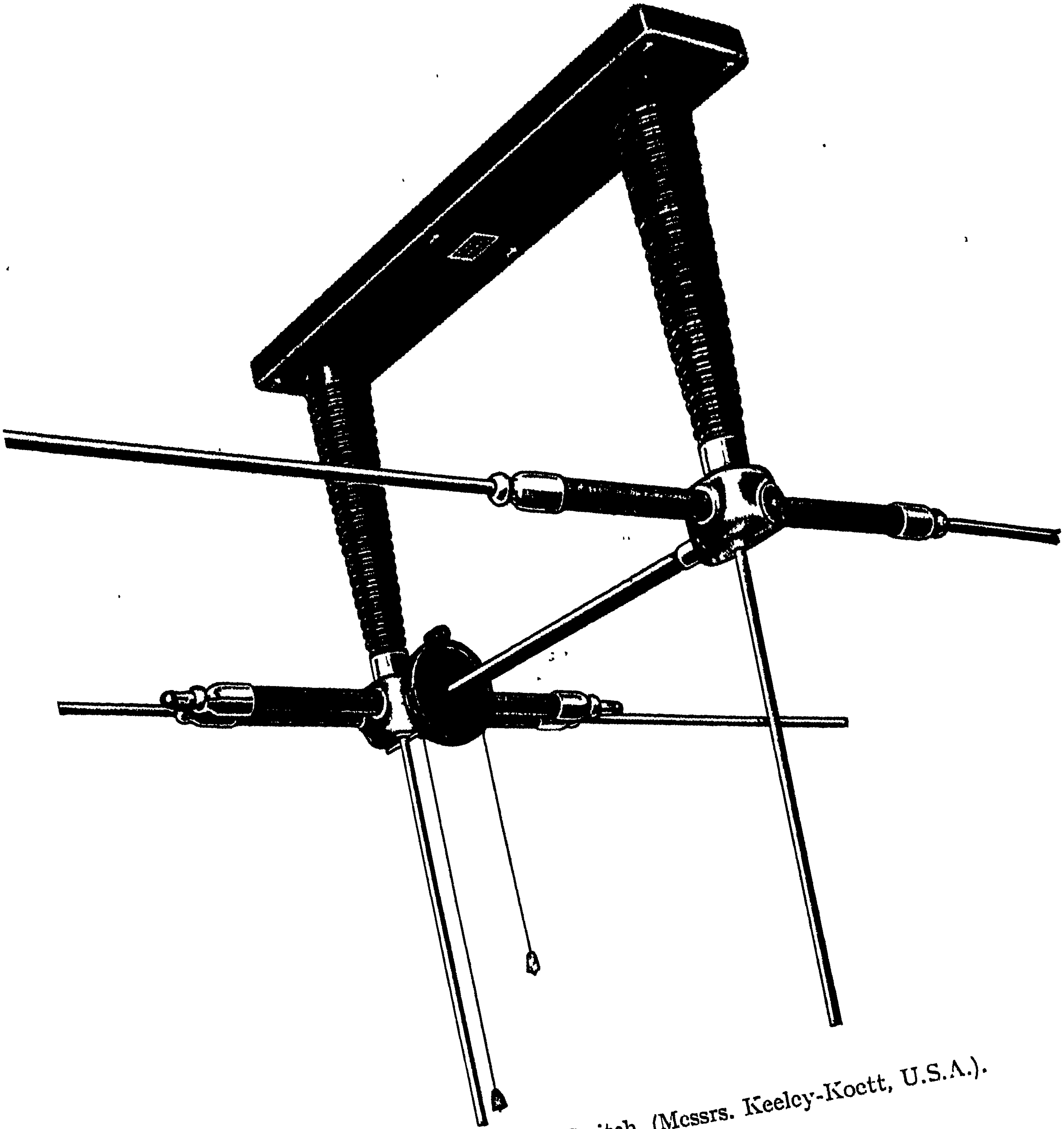


FIG. 460.—Change-over Switch (Messrs. Keeley-Koett, U.S.A.).

[To face p. 467.

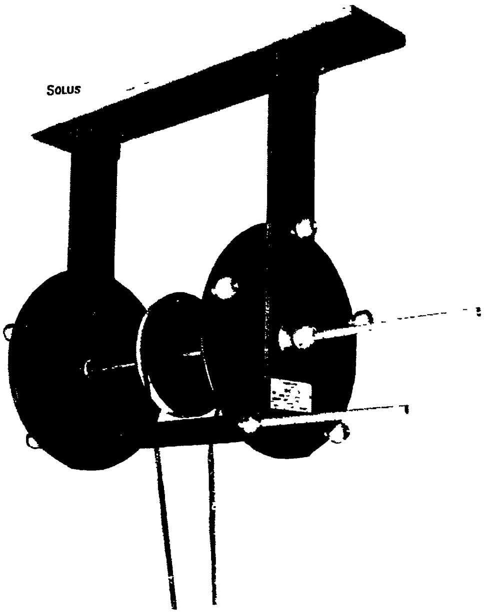



FIG. 461.—Three-line Change-over Switch (Messrs. Solus).

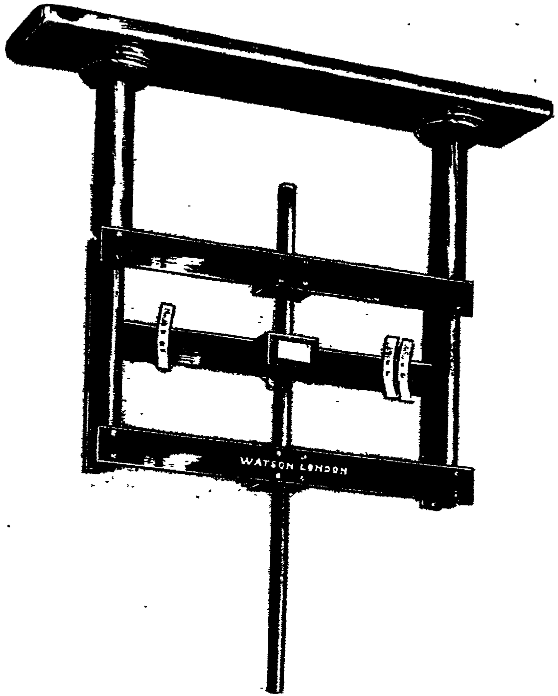



FIG. 462.—Sliding Type of Change-over Switch (Messrs. Watsons).

[To face p. 467.

local circumstances, as regards convenience of use, etc. As a general principle all apparatus should be given a specific position and be always, within reason, kept there.

Temporary leads to the apparatus should not be permitted, each apparatus having its own rheophore connections which, when not in use, are released, and are so always kept out of reach of accidental contact. Down leads to couches which are unavoidable should be encased in insulating sleeves (see p. 392, Vol. III.). One method of avoiding such down leads in an inconvenient situation is to take high-tension leads from the aerial system down to the floor in some convenient place and then to conduct these by high-tension cable beneath the floor, to again rise actually beneath the table itself. Such a method overcomes all risk of contact in the dark, which is the danger of the usual down leads.

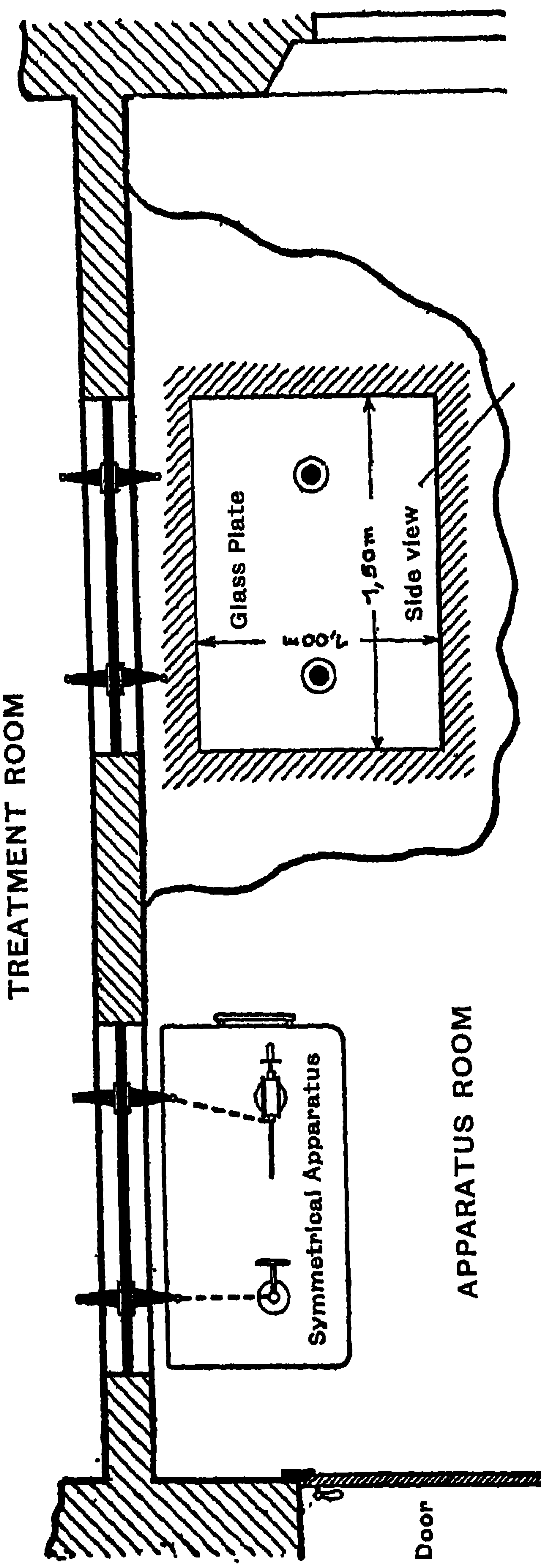



Fig. 465.—Lead-through Window.

Little more need be said concerning these apparatuses, but we have still to discuss the location of the high-tension generating plant itself.

It is the custom in England to mount this all within a wooden case, containing rotary converter (or synchronous motor), transformer and rectifying disc. This case is intended to be within the radiographic room itself. As a consequence we have excessive noise, noxious fumes from the rectifying apparatus and some considerable floor space occupied.

Perhaps the most objectionable feature is the noise and flashing of sparks, which try severely nervous patients and children.

This practice is being abandoned abroad and the actual high-tension plant is placed in a separate room. Such an example is seen in Fig. 465, where the high-tension leads to the X-ray tube pass *viâ* the window shown.

X-ray conductors *viâ* walls and floors. It has the advantage that it occupies very little space in comparison with the other methods described and avoids bare leads.

In the case where high-tension leads are led *viâ* floors the type of insulator shown in Fig. 468 is preferable to the panel insulator, as dust is liable to collect upon the latter (Fig. 467) and cause brushing or even short circuits. In this case the leads pass directly upwards at one end of the radiographic room and are then distributed. These leads, to avoid contact in the dark, should be surrounded by a frame having everywhere a clearance of 1 ft. or more and covered with " expanded metal " or some other wire guard which is earthed (see Fig. 482).

When it is impossible to follow this ideal arrangement of a separate high-tension room, the normal cased-in type of apparatus may be fitted with a chute and exhaust fan opening either directly into the atmosphere, or into a ventilator, to remove the fumes generated by the rectifying arrangement.

When the ideal method is followed a switchboard, to control the prime source of energy, is mounted upon the wall of the radiographic room, so that the apparatus may be operated from there, both by this switchboard and by the normal portable switchboard.

The only objection to this method is that there is some risk of the high-tension plant not receiving attention but, if this is done by routine, this does not occur. Conversely the open arrangement of the apparatus allows much better cleaning than when it is in a case, as it can be got at from all sides and not merely the front, as in the case of a wooden enclosed apparatus, standing usually against a wall. A main switch should always be fitted near the high-tension apparatus itself, and stringent instructions be given that this must be broken before the apparatus is touched, to avoid the risk of some person in the operating-room starting up the machine whilst it is being cleaned, with considerable risk to the cleaner.

A window between apparatus and radiographic room is very useful and can be covered, when required, by a shutter.

The objection to the installation of the high-tension apparatus in a cellar or room below the X-ray room is, unless high-tension cable can be used (which is not easily obtained in England), considerable floor space must be devoted to the Faraday cage surrounding the high-tension leads as they pass from floor to ceiling of the X-ray room (Fig. 482).

Albers-Schönberg in his Hamburg Hospital (*q.v.*) and later Dr. Santé in his St. Louis City Hospital installation (*q.v.*), have evaded this objection by placing all the high-tension apparatus on the floor above and not below the X-ray rooms (Fig. 507).

The high-tension leads are then led directly downwards *viâ* the X-ray room ceiling (Figs. 508, 509, 512). All danger of contact is thus removed, particularly since at St. Louis the leads are only above the particular

plant, the space was still further cramped and the rooms soon became unhygienic, by reason of the brush discharge fumes, particularly since anti-corona connections were not then in vogue.

The modern type of treatment room is preferably a long room (see Fig. 469) along the distant wall of which the high-tension leads pass, a generating apparatus, of sufficient power to operate a number of tubes, being used.

Where separate generating plant is used the common apparatus room of ample dimensions is behind, and an operator's gallery in front (Fig. 469).

The practical objection to this method is that it requires one attendant per patient. A much better arrangement is to arrange several of these treatment places so that each operator can control several treatments.

In the " Multivolt " apparatus (see p. 341, Vol. III.) the X-ray tubes are completely enclosed and the operators walk freely amongst the patients, although protection from scattered radiation would still be advisable and is often adopted in the form of a screen.

The operators, in the former type of treatment room, are protected by barium plaster walls with sliding doors to every compartment. To prevent these doors being left open during actual treatment a relay can be fitted which does not allow the apparatus to be operated until the door is closed and contact of the low-tension circuit so made.

At each treatment couch, so that it is easily accessible to the patient without movement, an alarm bell, or even a push switch operating a relay circuit putting the apparatus out of use, should be installed.

The partitions between patient and patient have the purpose of preventing cross-fire scattering from patient to patient and also to preserve privacy of each patient. For this purpose a movable wood-lead screen is sufficient, but it is usually cheaper to employ barium plaster walls of about 1 in. to 2 in. thickness. These walls need only be 5 or 6 ft. high, and so the closed-in feeling of cubicles is not obtained by the patient with the advantages of the cubicle system (see Fig. 502).

Beneath each patient, if the room is not upon the ground floor, or a floor built on barium cement, a lead plate, covered by a rubber mat, should be placed to prevent radiation entering the room below.

Ventilation, lighting and heating follow as in the radiodiagnostic rooms.

Each cubicle has towards the operating gallery a sufficiently large lead-glass window to allow the patient to be entirely in view of the operator when the latter is seated at the control table.

Such windows should not however be larger than necessary for the above purpose. They should also not be so situated that they receive direct radiation, since it should be recognised rays striking the lead glass at an angle, have to pass *viâ* a greater thickness of glass and are therefore absorbed to a greater extent. For example, a glass 1 cm. thick and

(4) A large sink, sufficiently large to contain a tank-developing outfit, and if desired a thermostat temperature-controlled bath, with a copious supply of both hot and cold water.

(5) A floor, other than wood, and so sloped that any water which may be spilt will rapidly drain away. Wooden racks near the sink are useful.

(6) A plentiful supply of cupboards and benches, the latter draining back to the sink.

The particular accessory photographic apparatus is dealt with elsewhere, but where tank development is not used, a motor-driven automatic washing rocker apparatus is useful. This room should be protected

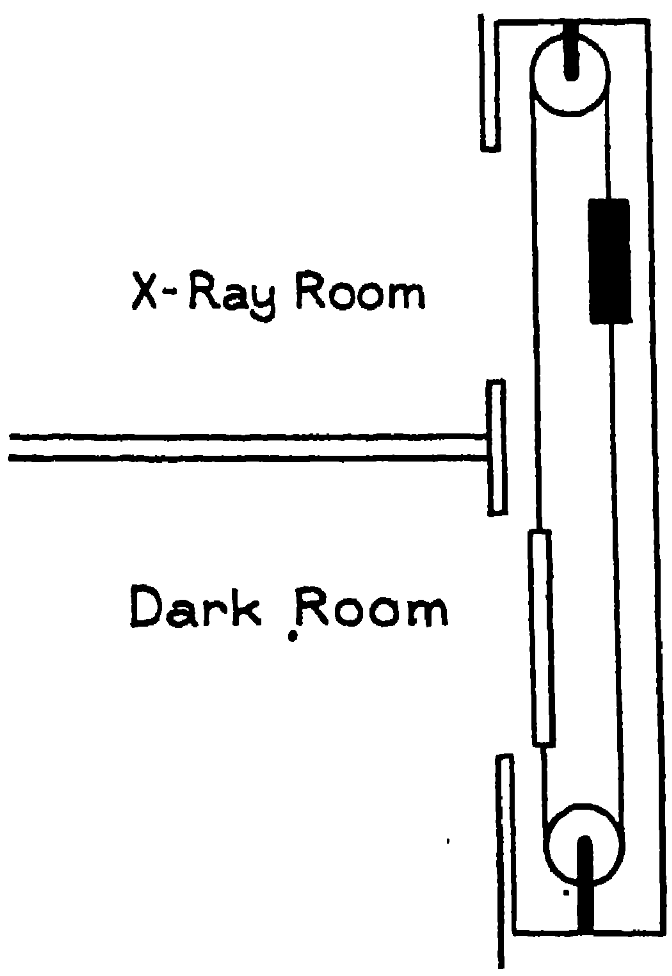



FIG. 470.—Plate Lift.

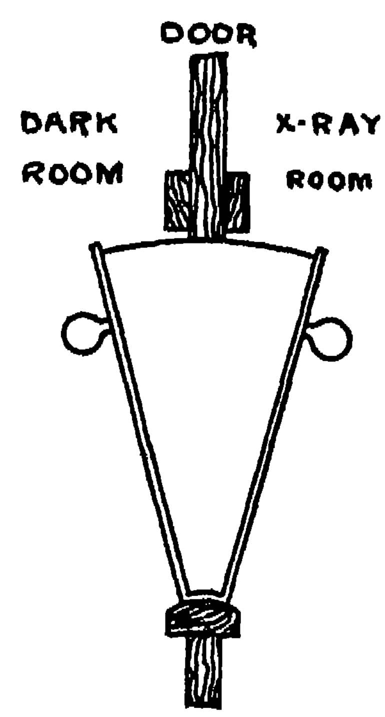



FIG. 471.—Plate Passer.

from the diagnostic or treatment rooms by a barium plaster wall and, where this is not possible, by a rendered wall or lead sheeting.

To avoid the necessity of opening the door to pass plates backwards and forwards between this room and the diagnostic room, a plate passing apparatus may be used.

A revolving form of such a plate passer, similar to the revolving door shown on p. 483, occupies usually too much space.

When the developing room is above or below the radiographic room a flat slide arrangement (Fig 470), operated like a lift, may be employed, or, at the same level, a similarly contrived slide, into which plate cassettes are dropped.

A very neat arrangement, made for the author, is shown in section in Fig. 471. This does not occupy much space and is very simply operated by movement to and fro. In all such cases the side of the plate passer towards the diagnostic room should have lead protection, in case a plate is not immediately moved or is resting there for use.

Such a room offers no special features and is suitably equipped with writing bureau, etc. It will include a suitable viewing box and stereoscopic viewer to permit discussion of diagnostic plates. As other fittings we have a telephone and, in the case of extensive treatment clinic, call bells to allow an operator to call the medical officer responsible without leaving the patient.

In a small department a lead-glass window, allowing a view of the treatment or radiographic room, or both, is very useful.

Where much diagnostic work is being carried out, a separate room to view plates and write reports should be used by the diagnostic radiologist, who is only too apt to make absurd errors and omissions if others are using the room and distracting his attention.

Dr. Santé of St. Louis has adopted a very useful device in his hospital. In the senior radiologist's room there is a system of lamps, each of which is connected with a particular high-tension X-ray transformer primary circuit. When the transformers are in use these lamps are illuminated and the radiologist can at once tell, without leaving his room, where and when work is being carried out in his department.

## 8. ACCOMMODATION FOR LAY STAFF

This will again depend upon the extent of the staff and, if large, the sister-in-charge may have a separate room to the assistants. Call signals may be fitted.

## 9. WASHING AND LAVATORY ACCOMMODATION

This will be necessary for patients, and separate facilities will be required for the medical and lay staff, unless elsewhere provided in the hospital.

## 10. MUSEUM AND DEMONSTRATION ROOMS

These are only necessary in the larger teaching hospitals and the museum will comprise post-mortem specimens for comparison with diagnostic findings. A radiological library is an important adjunct. In the large institution at Hamburg the previous day's prints, when dried, are displayed in one or more windows, which serve in place of viewing boxes. Members of the non-radiological staff may enter to view and discuss the radiological findings. Such rooms should be placed near the entrance of the department, so that it is unnecessary for non-radiological staff to pass by the actual working rooms and so cause disturbance.

## GENERAL CONDUCT OF A LARGE RADIOLOGICAL DEPARTMENT

The staff of an X-ray department will naturally depend upon the nature and extent of the work. If much therapeutic work is carried out, the whole-time attendance of a radiologist is necessary, since such treatment should only be carried out by a lay assistant when a qualified superior is actually in the hospital. If this is not arranged, in the event of legal claims for burns, etc., the hospital is liable to be in a very much worse position to resist such claims than if a qualified radiologist had been present.

Barclay has given the following table as suggestive of the X-ray staffs necessary for hospitals of various sizes ;—

STAFFING AN X-RAY DEPARTMENT

| Cottage Hospital | Hospital up to 60 beds | Hospital up to 200 Beds. | Large General Hospital. | Large General Hospital with Teaching School. | Duties. |
|---|---|---|---|---|---|
| 1 Honorary M.O. | 1 Honorary M.O. | 1 Honorary M.O. | 1 Honorary M.O.<br>1 Junior M.O. | 2 Honorary M.O.'s<br>2 Junior M.O.'s<br>1 Physicist | General organisation and teaching.<br>Fluoroscopic examinations.<br>Reporting on plates.<br>Prescribing for treatment cases.<br>Physics of X-ray Dept. |
| | | 1 Assistant | 2 Assistants | 2 Assistants<br>1 Assistant | X-ray treatment (ordinary).<br>X-ray treatment (intensive). |
| | 1 Radiographer | 1 Radiographer | 1 Radiographer | 1 Radiographer<br>1 Mechanic | Radiography.<br>Repairs to apparatus, etc. |
| | | | 1 Photographer | 1 Photographer<br>1 Photographic librarian | Developing negatives.<br>Prints and lantern Slides.<br>Clerical work, museum.<br>Clerical work, routine. |
| 1 Nurse | 1 Nurse | 1 Nurse<br>1 Sister | 1 Clerk<br>1 Nurse<br>1 Sister<br>1 Charwoman<br>1 Porter | 1 Clerk<br>2 Nurses<br>1 Sister<br>1 Charwoman<br>1 Porter | Attending to patients.<br>Responsible for dept.<br>Cleaning<br>Porterage. |

The success of a radiological department will depend very largely upon the chief. From the radiological aspect it is often found that the second radiologist is the more competent radiologist and the chief is more the man of affairs who can approach his committee and obtain funds for his department, and suitably influence funds from outside sources.

On the other hand, the chief may be a practical radiologist of great ability and in some cases conducts all the major investigations himself.

In the former case the actual radiological work done by the chief may be little or nil, and, in such a case, for success of his department he is well advised to refer all clinical inquiries to the radiologist who has actually carried out the examination.

carried out the examination may have not the slightest doubt such an ulcer is present. The wisest course is therefore to refer contradictory clinical enquiries, which always occur in course of time, to the particular radiologist who has actually carried out the examination. It is not suggested that open discussion is not good. Cases will occur in which radiologists themselves differ, and the discussion of such differences is to the general good. It does however not add to the prestige of the department if it becomes generally known that the various radiologists have different views, and in time all the radiologists so suffer.

It is not suggested an entirely erroneous report should be backed up by the chief, but it is suggested that it is always the radiologist who actually examines the case who should have the last word.

The radiologist should also not give way to pure clinicians as a matter of habit. The radiologist is more respected who can meet the clinicians upon their own ground.

It is not uncommon for the question to arise as to whom the X-ray films belong, *i.e.*, clinician, radiologist, or the patients (if these have paid any fee). This matter has been decided on legal grounds abroad, and it has been ruled that the films are the property of the radiologist, and not of the patient or clinician.*

Naturally in a hospital the films purchased by the hospital must remain the hospital's property, but the copyright and any permission for reproduction is dependent upon the radiologist.

All cases of treatment should be left, by the non-radiological staff, to the radiologist, as far as the dosage and nature of the treatment are concerned, as he is always the man legally responsible and will have to meet any charge of negligence.

It is a good practice to make every diagnostic or treatment case sign a book, or form, to the effect that he wishes such treatment and consents to it. Such a signature has no value in the case of a legal action for gross neglect, but has a certain value in the case of accidental injury and has a very distinct value in the use of actions brought by hysterical persons for fancied injury due to X-rays. The radiologist, above all other medical men, has most need to belong to a medical protection society.

The form in which reports are made differ with the different hospitals. Some use very full forms upon which various details are ticked off and remarks made. An example of such a form used at one of the writer's hospitals is shown on p. 479.

The idea is an American one and, whilst the example shown merely relates to thoracic work (chiefly tubercular), various other suggested forms for abdominal, renal, work, etc., will be found in an article by R. D. Carman in the *American Journal of Röntgenology* for 1921, p. 372.

* Resolutions of The Radiological Society of North America, 1920 (*Radiology*, 9, p. 340, 1927), and of the Deutsche Röntgengesellschaft, 1912.

if at least one radiographer lives in the hospital, or a radiologist is always on call by telephone.

It is usually recommended that all assistants should be given at least a month's holiday and at least two half days free per week besides Sundays. Such a recommendation is not by any means possible in a smaller hospital, as this means the employment of two radiographers, with consequent increased maintenance cost.

Further it is questionable whether this is necessary. It is not uncommon for a radiologist or radiographer to attend several hospitals upon certain days of the week and it is well known they do so whilst at the same time engaging in private work.

It is therefore a moot point whether a hospital committee can be honestly requested to bear the ultimate cost or inconvenience of these half holidays, when it is by no means uncommon for radiologists and radiographers to themselves forego these relaxations and even to engage in private X-ray work elsewhere during such free afternoons.

The blood of all persons connected with a radiological institute should be periodically examined by the pathologist, say at monthly intervals. Until we have more definite data as regards white cell blood changes, due to electrical causes other than X-radiation, too great an importance should not be placed upon such changes, unless they are extreme and particularly, if they co-exist with red cell variations.

his death, conducted under the supervision of Professor Holthusen, to whom, in 1921, the author was indebted for his great kindness in conducting him over the building and explaining its admirable arrangements. During a fairly extensive tour of the chief Continental radiological

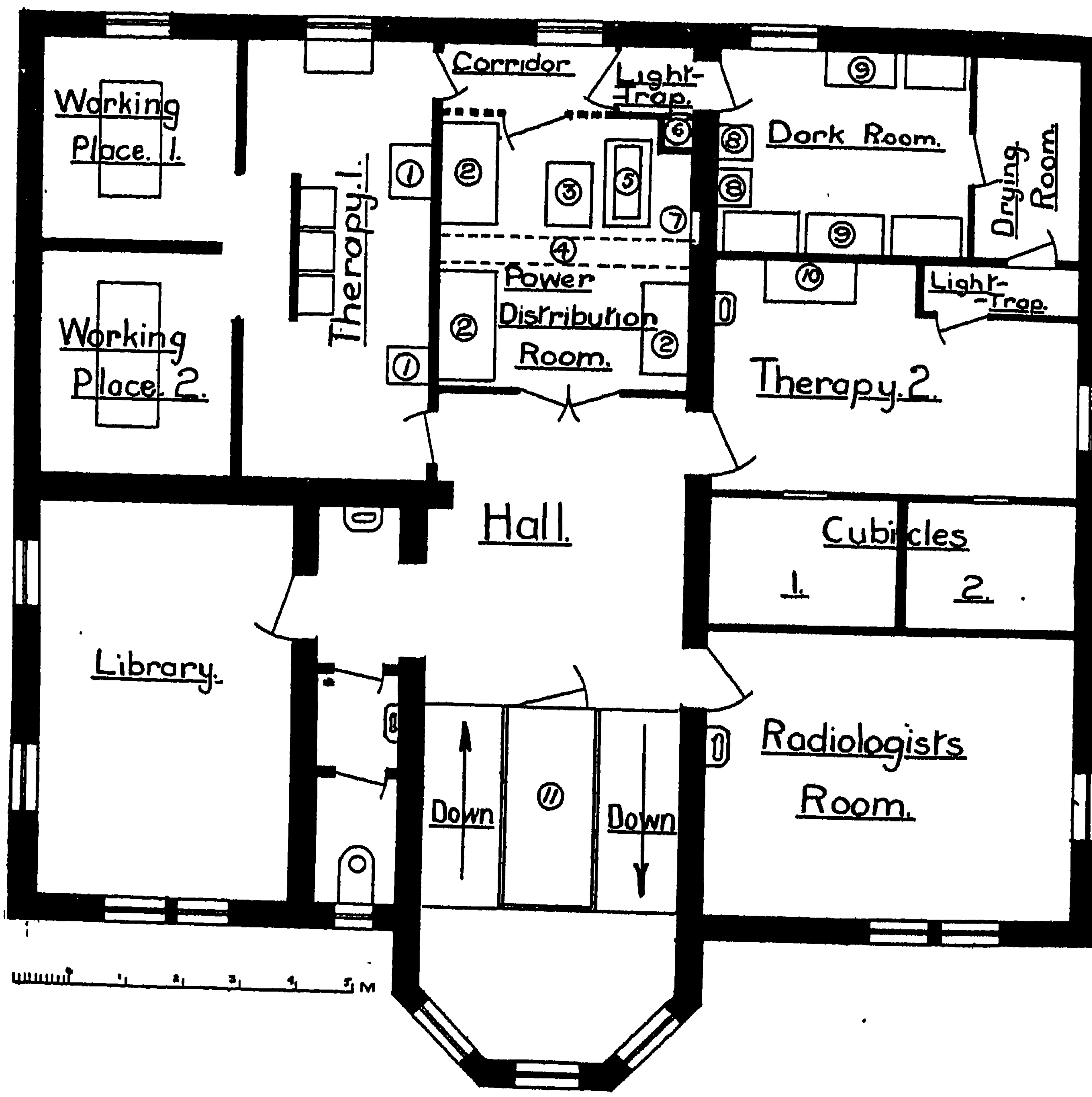



FIG. 473.—St. Georg Hospital, Hamburg (First Floor).

*Key.*—(1) Treatment apparatus; (2) rectifier apparatus for diagnostic rooms below; (3) high tension lead-through insulator from (2) to floor below; (4) conduit in floor for power mains; (5) rotary converter; (6) plate lift; (7) conduit for power mains in wall; (8) motors for rocking developing dishes; (9) cassette loading benches; (10) induction coil apparatus; (11) stretcher lift.

institutes the author found no institution which at this time could be compared to it for completeness of general layout. It still remains an example of the model X-ray institute.

This institute is a separate building of three floors, of which the ground floor is shown in Fig. 472 and the first floor in Fig. 473.

On the ground floor is a large room for radiographic work, a waiting

cliincal investigations, and permits a patient to be raised slowly by electrical means by pressure of a foot switch. It is fitted with a Bucky grid. As already mentioned, the third apparatus is for the orthographic bench on the floor above. The second place is for surgical work, *i.e.*, fractures and minor surgical operations, as pneumothorax, pneumo-peritoneum,

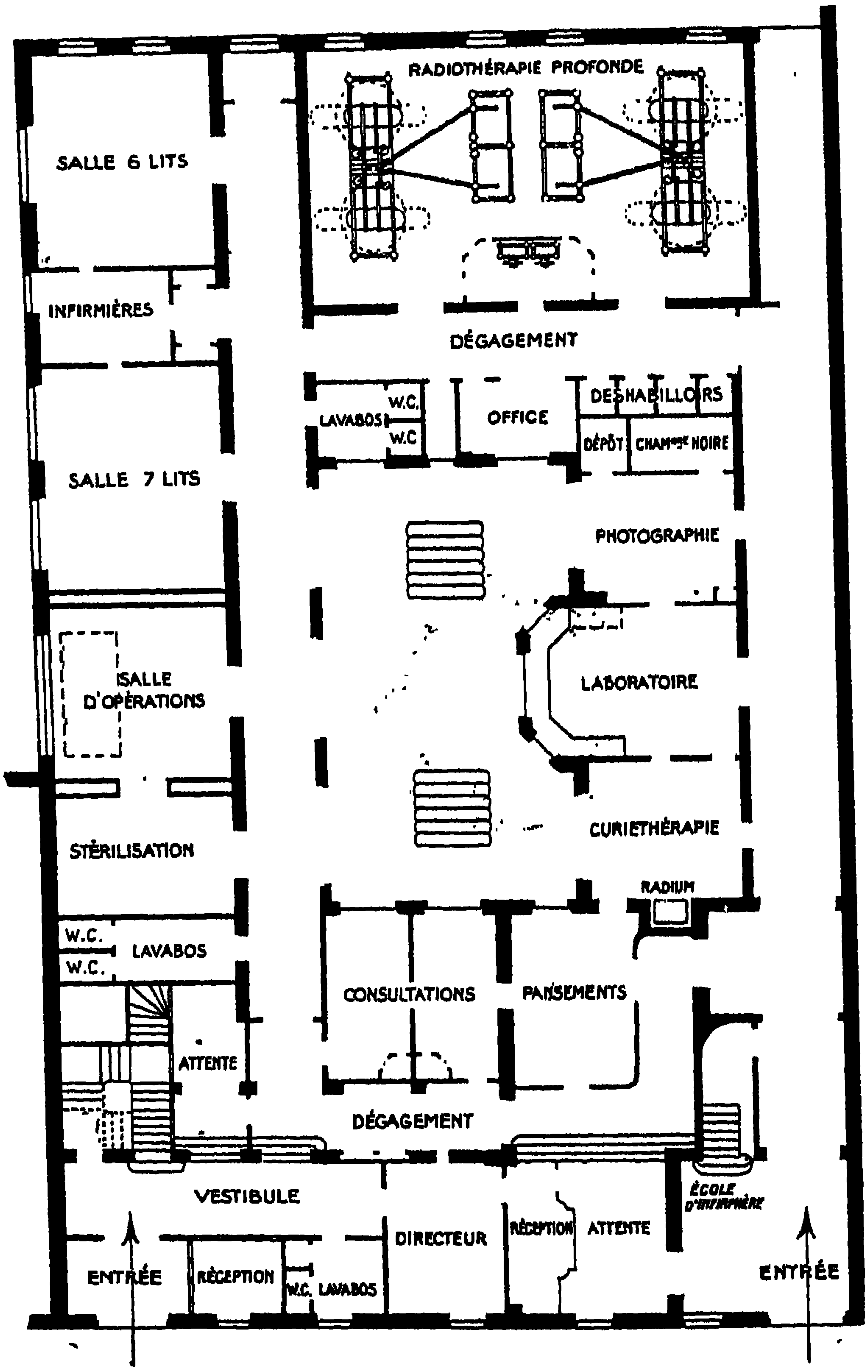



FIG. 474.—Nancy Anti-Cancer Clinic.

etc., work is carried out here. The fourth working place is for localisation work.

Entrance to the waiting-room from outside, on the patient's part, is provided without the need of entrance into the main hall.

In the museum are specimens and plates illustrating the whole course of the radiographic appearances of disease. The non-radiological hospital

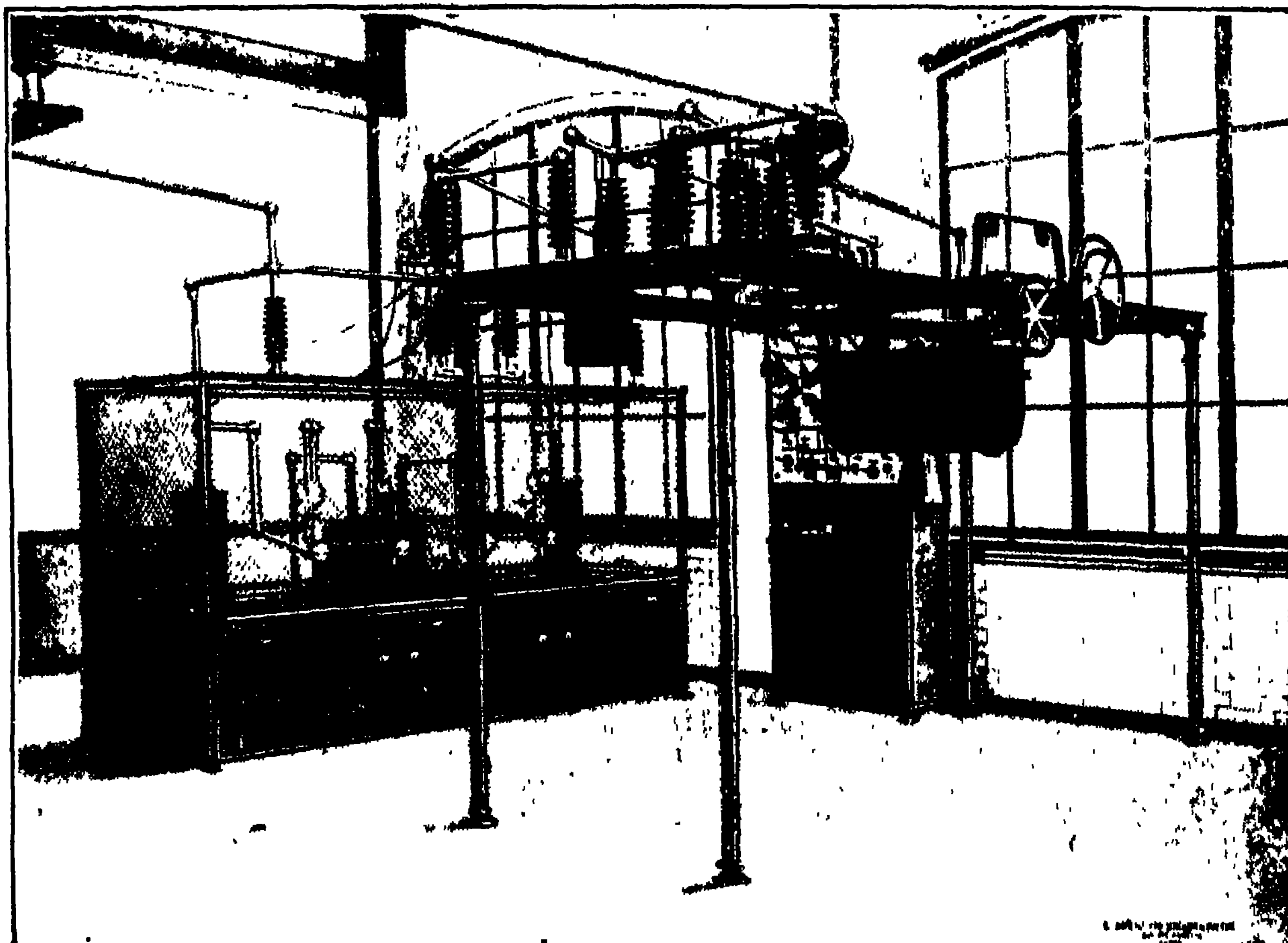


Fig. 475.—Treatment Room, Anti-Cancer Clinic, Nancy.

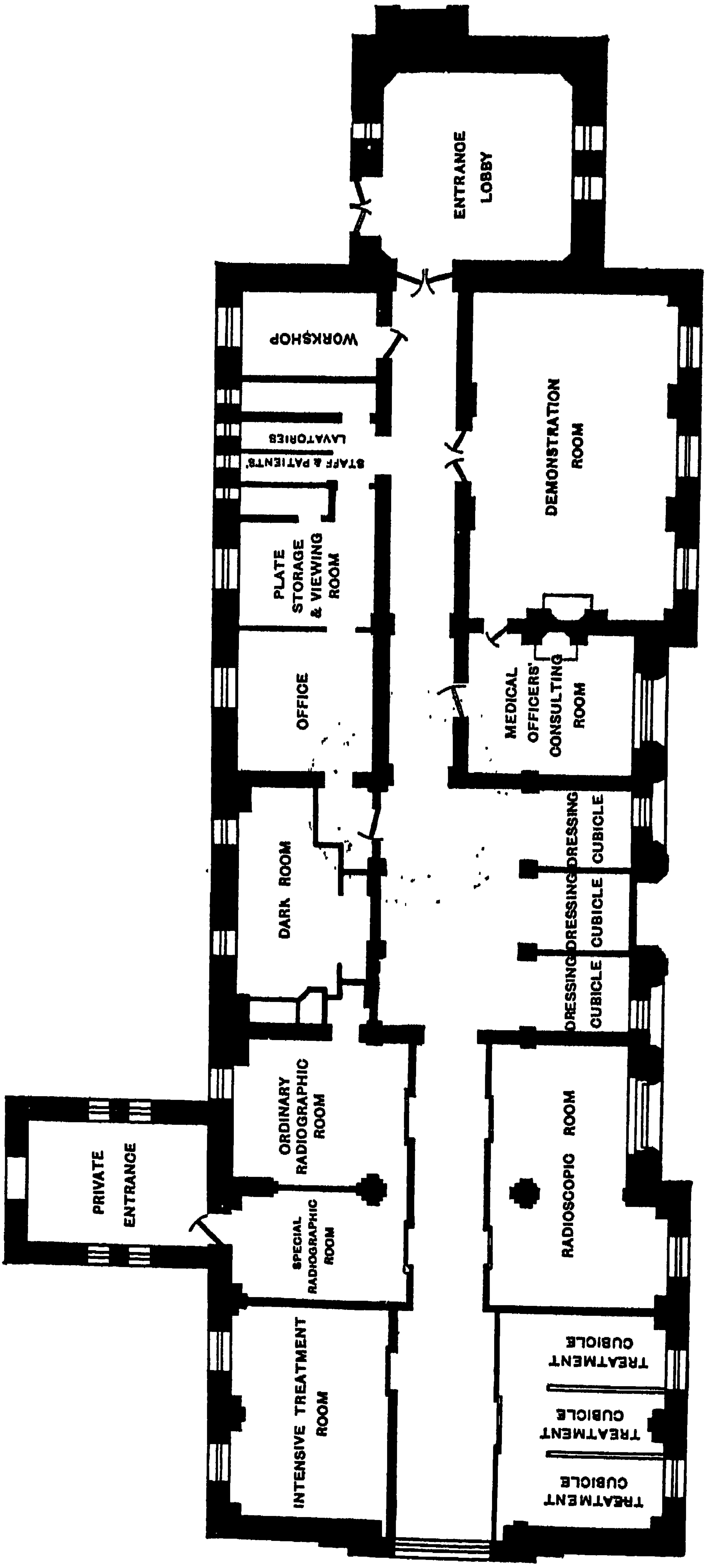



Fig. 477.—Plan of X-Ray Department, The Manchester Royal Infirmary.


FIG. 476.—Demonstration Room. X-Ray Department. The Manchester Royal Infirmary.

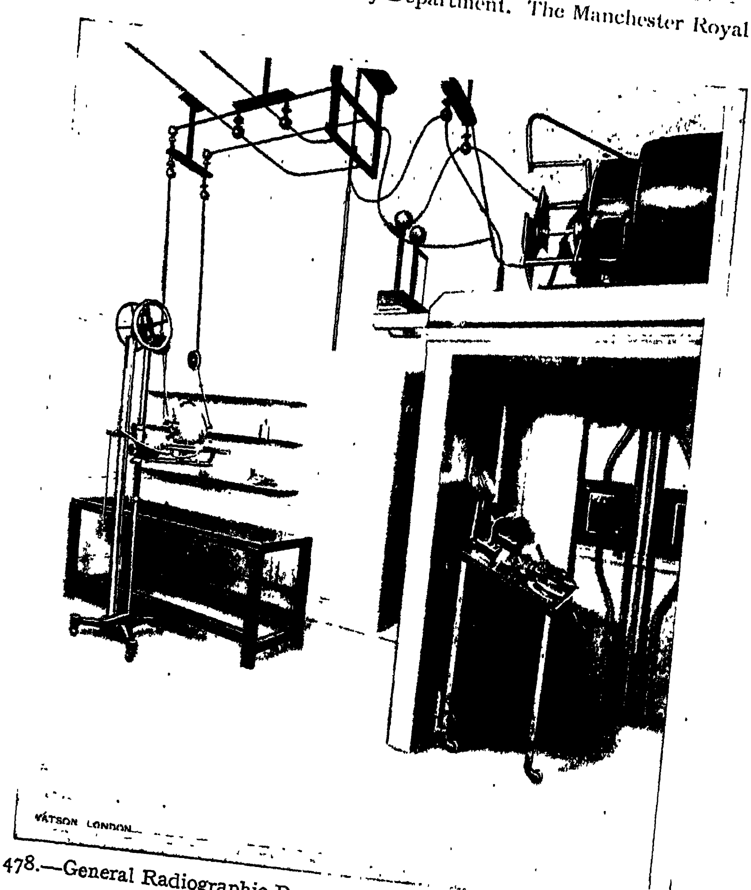



FIG. 478.—General Radiographic Room. X-Ray Department. The Manchester Royal Infirmary.

*To face p. 489.*]

cient flexible connection has been left to allow the switch-table to be operated in close proximity either to the screening stand or the couch. The overhead gear in this department is worthy of note, being completed in aluminium tubing and ebonite insulators mounted on mahogany frames. Two change-over switches are supplied in this department for isolating any individual piece of apparatus while the remaining fittings are in use.

In the *special radiographic room* there is a 2-kw. high-tension transformer for operating either the Coolidge radiator type tube or the dental tube. A tilting top couch similar to the one in the radioscopic room, and in addition to this, a dental chair is present. It is possible to remove conveniently the apparatus in this room to the wards for use when occasion arises.

The *general radiographic room* will be seen from Fig. 477 not to be entirely, but only partially, separated from the previous room by a pillar, which was part of the original building structure and could not be removed. A similar pillar is an obstacle in the radioscopic room.

In this room is fitted a table which has been built entirely for use with the Potter-Bucky diaphragm, the diaphragm proper running on rails immediately below the tunnelled aluminium couch top. The advantages of an instrument of this type in modern radiography hardly need emphasising at the present time. A simple couch operating in conjunction with the tube stand is also installed in this room. The high-tension generator, in this instance, is built into the room and the major portion is mounted on the top of the operator's protective cubicle (Fig. 478).

All the controls are installed in the cubicle, and after having arranged the patient and the tube, the whole procedure of taking a radiograph can be effected from the cubicle without the operator leaving this section. This system ensures that the operator will run the minimum possible risk from exposure to the X-rays.

The overhead system in this room is arranged as in the radioscopic room and is separated by overhead switches, so that each piece of apparatus may be isolated as required.

*The dark room* (Fig. 479) is worthy of special notice as illustrating an ideal type of dark room of large size, and not merely a closet adapted as a dark room, which is only too common in hospitals.

This dark room is arranged so that systematic development can be carried out on the temperature and time principles. Two complete sets of tanks which are thermostatically controlled to ensure even temperature are fitted along the wall, and a water supply is laid on to the surrounding tank. Draining racks and cascade plate-washing racks are also supplied to ensure the production of clean negatives. The lighting is by an indirect method, and instead of the usual ruby dark-room lamp, a green safe light has been installed, which allows a greater amount of useful but photographically safe light being available.

By this means, no undue out-of-balance load is thrown back on to the three line power line, and the voltage drop on the internal wiring system of the hospital has been considerably reduced.

A departure, in this department, which is unusual, is a separate supply of alternating current generated by a special self-boosting converter-generator, This feeds the Coolidge circuit of seven tubes in all the departments, with the exception of the deep therapy department. Each circuit is metered and, throughout the wiring system, check lamps have been installed so that the mechanic in charge can locate immediately the section of the circuit on which any trouble has arisen.

This separate supply of filament circuits is of importance, since the large machine is capable of giving a steady supply of filament current to all other filaments, when one particular filament is made or interrupted. In consequence the current *viâ* the X-ray tubes, and intensity of emitted radiation, is much more steady than when one small machine supplies each separate tube filament.

In this department there is an absence of the black or drab-coloured walls usually associated with X-ray departments. Throughout pleasing colours have been used, chiefly green and cream-coloured enamel being used for decorative purposes. The lighting is very carefully arranged and the ventilation system is very efficient.

Throughout the department the high-tension conductors are of the coronaless type, and by this means the objectionable fumes which arise from the production of nitric oxides and ozone on the aerial systems is reduced to a minimum. To ensure the minimum amount of overhead system being electrified at any time, the units in each department are controlled by high-tension switches which cut out the sections of the overhead system not in use at any time.

All the walls of the department are rendered with protective barium plaster.

This plaster was made of one-third each of commercial barium sulphate, portland cement and well-washed sand. A $\frac{3}{4}$-in. layer of plaster has a lead equivalent of 3·5 to 4·5 mm. of lead when tested with radium $\gamma$-rays. The treatment cubicles are plastered on both sides, giving a total plaster thickness of 1·5 in. and an average protective value of 8·5 mm. of lead. All doors are lead lined and of the sliding type.

The X-ray installations were carried out by Messrs. Watsons. The remaining features of the installation are evident from the plan.

## THE ELECTRICAL DEPARTMENT, THE EAST LONDON HOSPITAL FOR CHILDREN

It has already been stated that the division of X-ray installations into those suitable for private use, hospital use, etc., is artificial, and for all

installations, there are certain guiding principles as regards protection, to which all should conform, as far as circumstances permit.

As an example of an installation, suitable for the smaller type of non-teaching hospital, the following installation will be of interest particularly as while based on Continental standards, it represents the first use in England of ferro-barium concrete construction (as distinct from barium plaster) of protective walls and the installation of the high-tension plant below the X-ray room, features which have been adopted in still later installations in Great Britain, one of which, that of the Royal United Hospital, is also due to the writer.

This hospital has 134 beds and a very large out-patient and casualty department.

The electro-therapeutic department comprises the following rooms:

(1) X-ray room (with dark-room and apparatus room).

(2) Ultra-violet radiation room (double-carbon arc).

(3) Ultra-violet radiation room (treble mercury-vapour arcs).

(4) Gymnasium.

(5) Massage and electrical treatment room.

In addition to diagnostic X-ray work, a fair amount of X-ray treatment work is carried out for superficial skin diseases, tubercular sinuses, etc., and for deep-lying pathological conditions, such as lymphadenoma, splenomegaly, enlarged mediastinal glands, by means of filtered radiation.

In the ultra-violet light rooms over 500 out-patient treatments per month are given. This number is expected to be very considerably increased, in the immediate future, as a result of carrying out treatment work for the L.C.C. tuberculosis centres.

In addition to out-patient treatment thrice a week, in-patients are radiated by carbon arcs twice a week, and numerous special treatments are given in the more severe cases, with mercury-arc lamps.

The ultra-violet light treatments are chiefly for rickets and allied malnutrition conditions, very prevalent in the surrounding poor neighbourhood. Skin affections are also treated, and very good results have been obtained with acne, chronic eczema and lupus.

The installation of the department involved very considerable structural alterations, costing about £800. In addition, the apparatus cost approximately £700, making a total of about £1,500. This cost would have been considerably more had the constructional and installation work not been practically wholly carried out by the hospital engineer (Mr. Greenway), which resulted in a very great financial saving to the hospital.

The general layout of the department is shown in the plan.

*The X-Ray Room* (Fig. 482).—In installing this room the Continental practice, of installing the high-tension generating apparatus outside the actual X-ray room, was followed. This results in the absence of danger from shock, the removal of nitric oxide fumes due to the high-tension

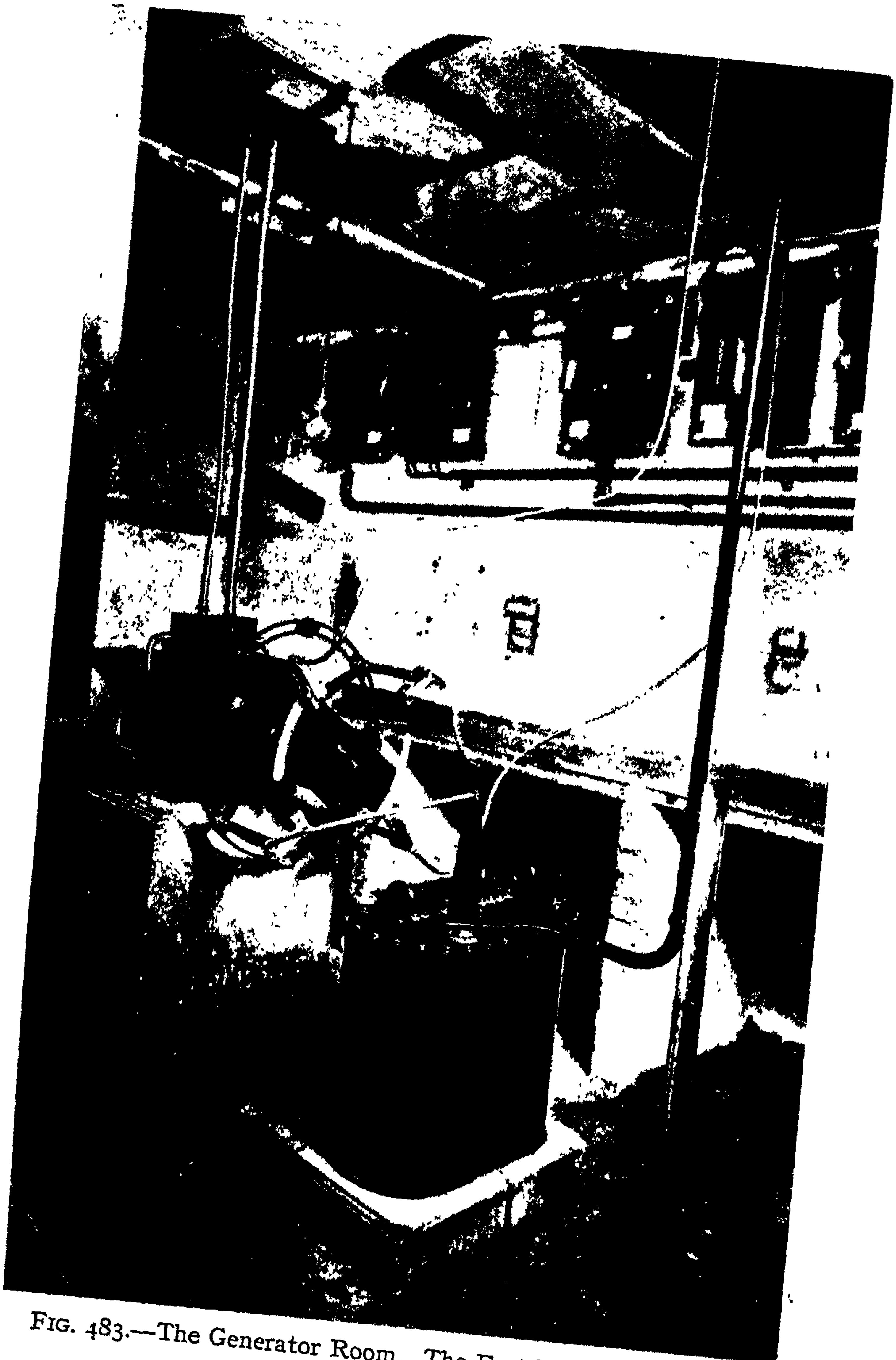


FIG. 483.—The Generator Room. The East London Hospital.

undercouch tubes, and a combined couch and screening stand. The latter is normally in the upright position for use as a screening stand. Treatment work, is however, carried out upon it in its couch position. This allows urgent radiographic cases to be treated upon the other couch with only momentary interruption, by means of the change-over switch, during treatment work.

The high-tension circuit is controlled by a portable switch table, fitted with time-switch, and foot-switch operating the ceiling lights. A motor-driven Bucky-grid is installed, and a modern tube stand.

A "light-lock" is present, which permits entry to the X-ray room during screening without the entry of light. The normal door is very wide, to allow easy ingress of stretchers.

The X-ray room was formerly part of a larger room, now comprising the X-ray room, dark room, and mercury vapour ultra-violet light room (also used as an office). To give efficient protection to the staff in the office and to plates in the dark room, the division was made by means of a reinforced barium concrete wall. This wall, weighing some tons, is supported upon a 33 ft. 6 in., 10 by 6 in. steel joist, with upright steel reinforcement, and is 14 ft. high. The thickness averages 5 in., and the protection is such that it is believed that no existent X-ray apparatus can produce radiation able to penetrate this wall. This protection is additional to the 3-mm. lead equivalent of the apparatus tube boxes. The total cost, labour, steel and concrete, was just over £50, much cheaper than a less protective lead lining. The wall was erected by the hospital engineer. A very large cupboard is provided for tubes, bandages, etc., and X-ray films are stored in the large cupboard (originally a main entrance) and so protected by the barium wall from stray radiation.

*The dark room* comprises a large sink, containing the tanks for development, table, abundant shelves, electrical fittings for electrically heating the room and to heat the developing solutions, and for normal and red lights operated either at the sink or the door. A swivel trap (Fig. 471) in the door allows plates to be passed to and from the X-ray room without the door being opened. The X-ray and dark room windows are fitted with perfectly light-proof stuff blinds in wooden frames, with a non-luminous ventilator above.

*The Mercury Vapour Lamp Room.*—This, when the ultra-violet lights are not being used, is also used as a general office. A lead-glass window allows protection to be obtained, since X-ray treatment work, when in course in the X-ray room can be observed from this room. Equally this window allows ultra-violet light treatment to be controlled from the X-ray room without the operator himself undergoing ultra-violet radiation.

The ultra-violet light apparatus comprises :—

(1) Two suspended mercury-vapour lamps. The position of these lamps above ground (or table), is conveniently controlled by the

From this room opens off a large cupboard (previously the X-ray dark room), in which patients' clothes may be hung whilst they are undergoing treatment.

Since the arcs are open arcs, and there is, therefore, a *theoretical* risk of fire, the doors are made to open outwards.

*Ventilation, etc.*—The X-ray room and carbon-arc rooms, and, indirectly, the mercury-vapour arc room, are ventilated by air chutes built into the ceiling and going to a common trunk on the roof of the department, where a large electric fan in a housing gives forced ventilation, under control from the department.

For heating and power purposes, all the rooms of the department are provided with power plugs, so that accessory electrical apparatus, and electric stoves, can be used at will.

All the main switches, meters, etc., are collected in the apparatus room below the X-ray room. A switch in this room breaks the circuit to the X-ray generator, so that there is no risk of this being operated from the X-ray room above whilst it is being cleaned.

All floors are of polished " Marbolith," which is largely non-conducting. Windows in the X-ray and ultra-violet rooms, and the cloak room, are fitted with properly constructed black lightproof blinds.

*The gymnasium department* comprises plinth, horizontal bars, climbing bars, and footprints. It is intended for remedial exercises for old anterior-poliomyelitis and analogous cases, as well as a gymnasium for the nursing staff.

When not in use as a gymnasium it serves as a waiting-room for the whole department. By means of the " light-lock," entry can be obtained from this room to the X-ray room whilst screening is in progress.

*Massage Department.*—The massage (and electrical treatment) room comprises couches and various apparatus for electrical treatment as follows: " Plurostat," for galvanism, faradism and cautery; " Galvanoset," with coil attachment, for faradism; a faradic coil and a radiant heat bath. Two plug sockets allow the apparatus to be used whenever desired.

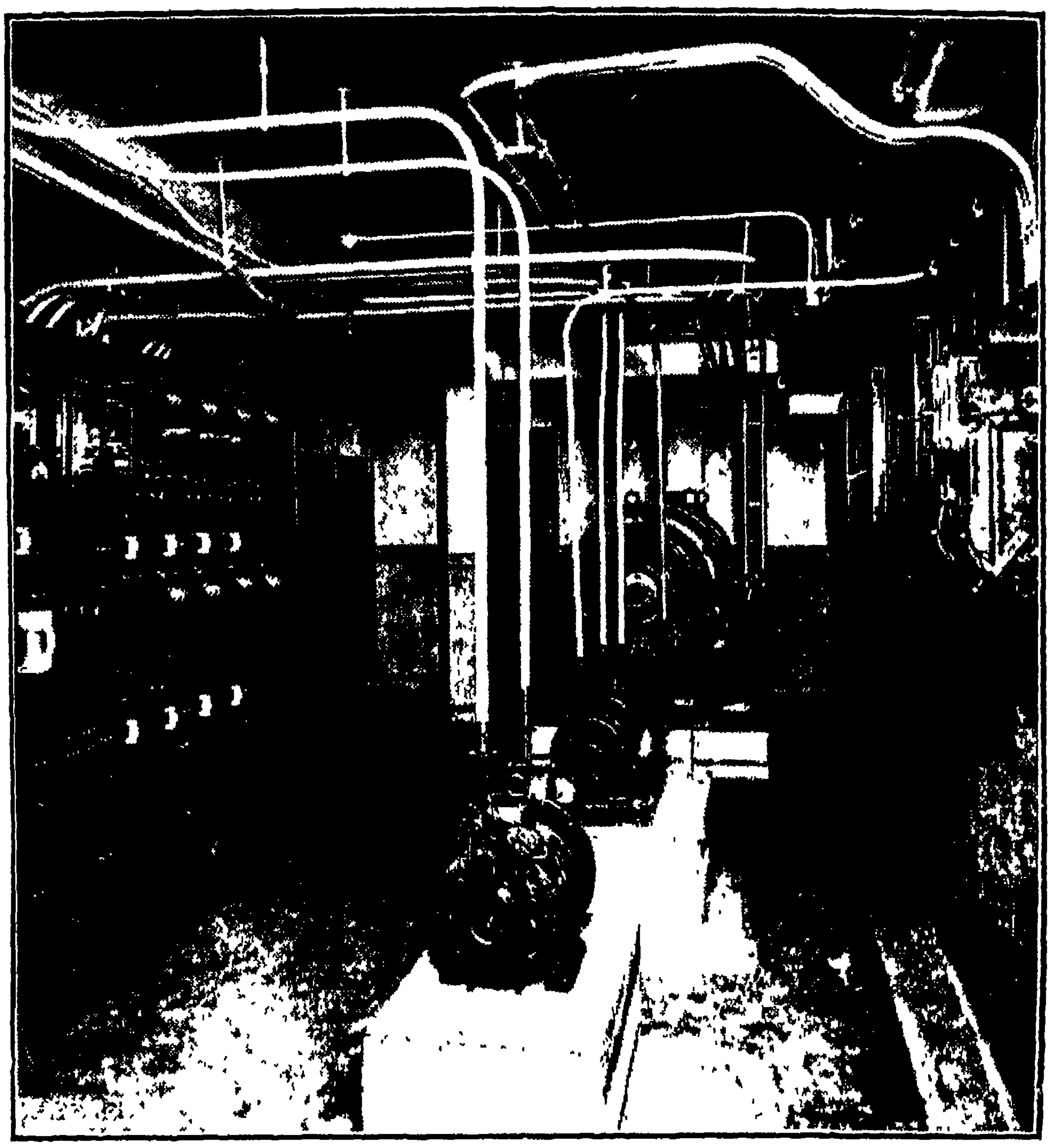


FIG. 485.—Motor Generator Room, Basement. The Edinburgh Royal Infirmary.

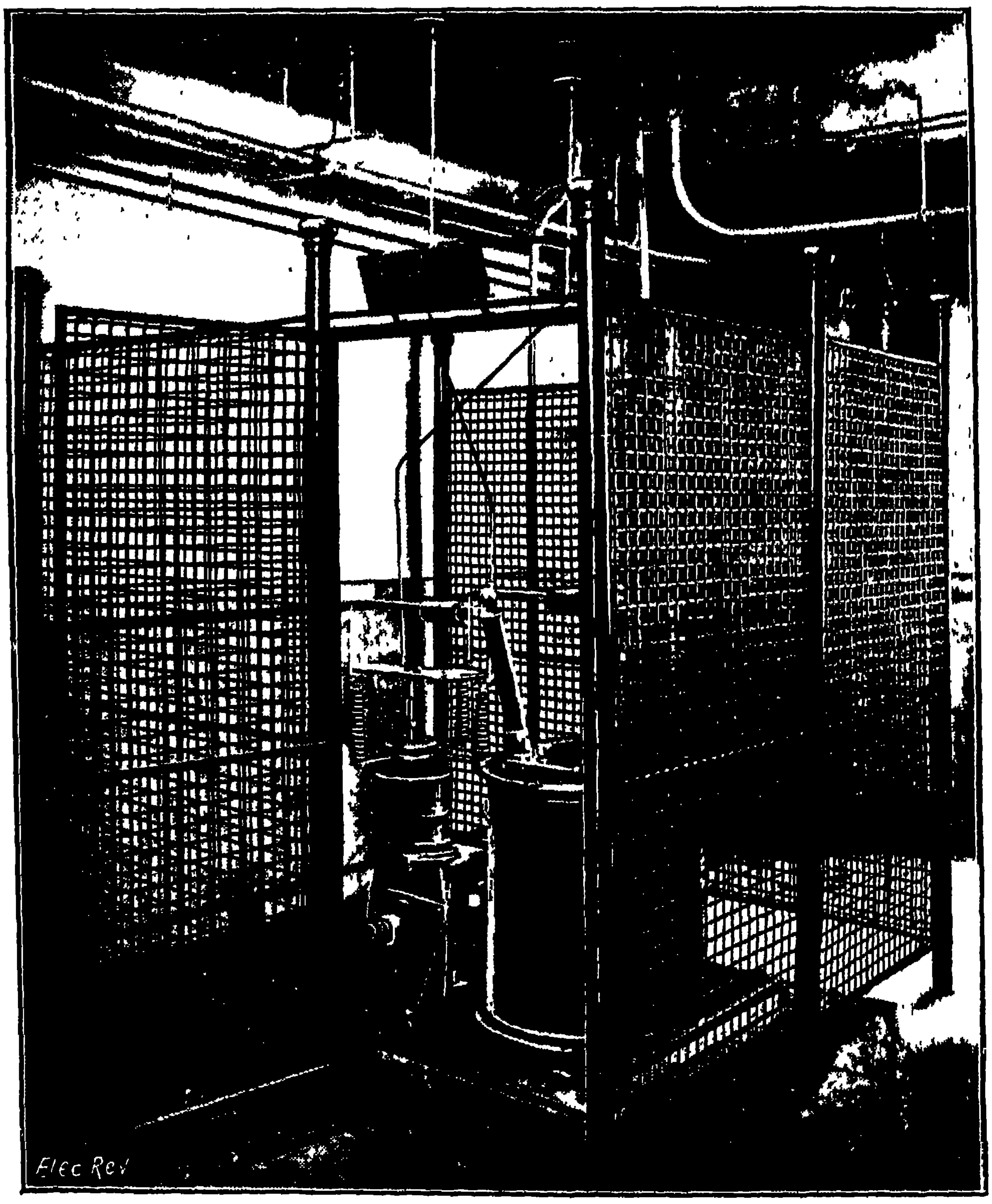


FIG. 486.—X-Ray Transformer and Rectifier (10 milliamperes at 150,000 volts). The Edinburgh Royal Infirmary.

*To face p.* 499.]

current and a 3-kw. direct current/alternating current rotary converter, intended to provide, if necessary, an emergency energy source. The local supply is three-wire 460-volt direct current, which directly drives the large rotary converter and is split to supply the lighting of the department at 230 volts. All this supply plant is controlled by a large switchboard (Fig. 485), which includes a Tirrell regulator, the purpose of which is to regulate automatically any voltage variation of the rotary converter as the X-ray plant is thrown on or off load, which would otherwise cause variations of X-ray emission from other apparatuses also in operation.

Within this machine room are also three high-tension transformers, each with a secondary output of 100 milliamperes at 150 kv. peak value. The secondary leads of these transformers pass *viâ* porcelain floor insulators to the floor above, where they are controlled by trolley type switchboards. Each transformer is enclosed in an expanded metal cagework (Fig. 486), on the outside of which is an illuminated sign, that lights up, immediately the apparatus is rendered alive from the room above. Also in the basement are three accumulator batteries for the supply of direct current, to cauteries requiring 10 to 20 amperes, and to various apparatus, as examination lamps, throughout the building. It is arranged for one of these batteries to be on load, whilst another is fully charged and the third is on charge.

The ground floor, devoted to X-ray work, comprises the following chief rooms, three radiographic and radioscopic rooms, a deep therapy treatment room, a superficial therapy treatment room, a room containing emergency diagnostic apparatus, a lecture room, laboratory, film store, dark rooms, the senior radiologist's room, and various rooms for waiting patients and the medical and lay staffs. The patients are received at the office next to the entrance door and sent to waiting rooms prior to being received in the diagnostic and therapy rooms.

The *deep therapy room* equipment is a Gaiffe-Gallot 225-kv. 10 milliamperes constant potential apparatus (p. 358), actuating two oil-immersed Coolidge tubes (Fig. 487), which may be used either singly or together. The protection of the oil containers is 5 mm. of lead.

All the rooms of the radiological department are lined with tongued and grooved barium blocks, having a protective equivalent of at least 4–5 mm. of lead.* The switch gear for the deep therapy apparatus is located outside the treatment room (Fig. 488) to avoid danger of scattered radiation to the operator, who has the patients in full view *viâ* large lead-glass windows, having an equivalent protective value of 3 mm. of lead. The doors are covered with lead sheet of 3 mm. thickness.

*A superficial therapy room* provides for treatments, such as of tinea. A

* The composition is 1 part rough sand, 2 parts engine ashes, 1 part Portland cement, 3 parts barium sulphate, in slabs 24 × 12 × 3 inches thick, and rendered with ⅝ inch plaster composed of 3 parts rough sand, 1 part Portland cement, and 1 part barium sulphate.

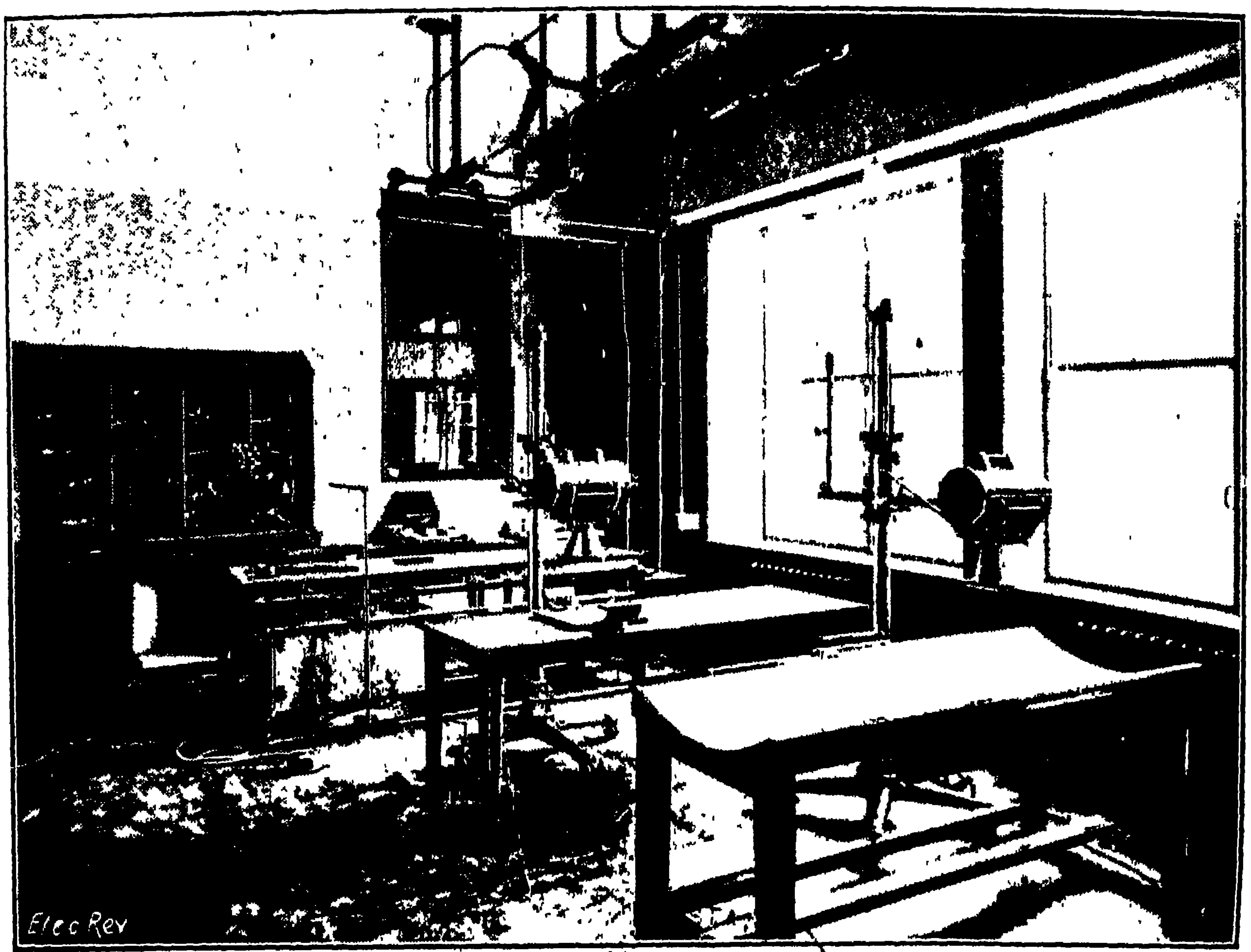



FIG. 489.—General Radiography Room. The Edinburgh Royal Infirmary.

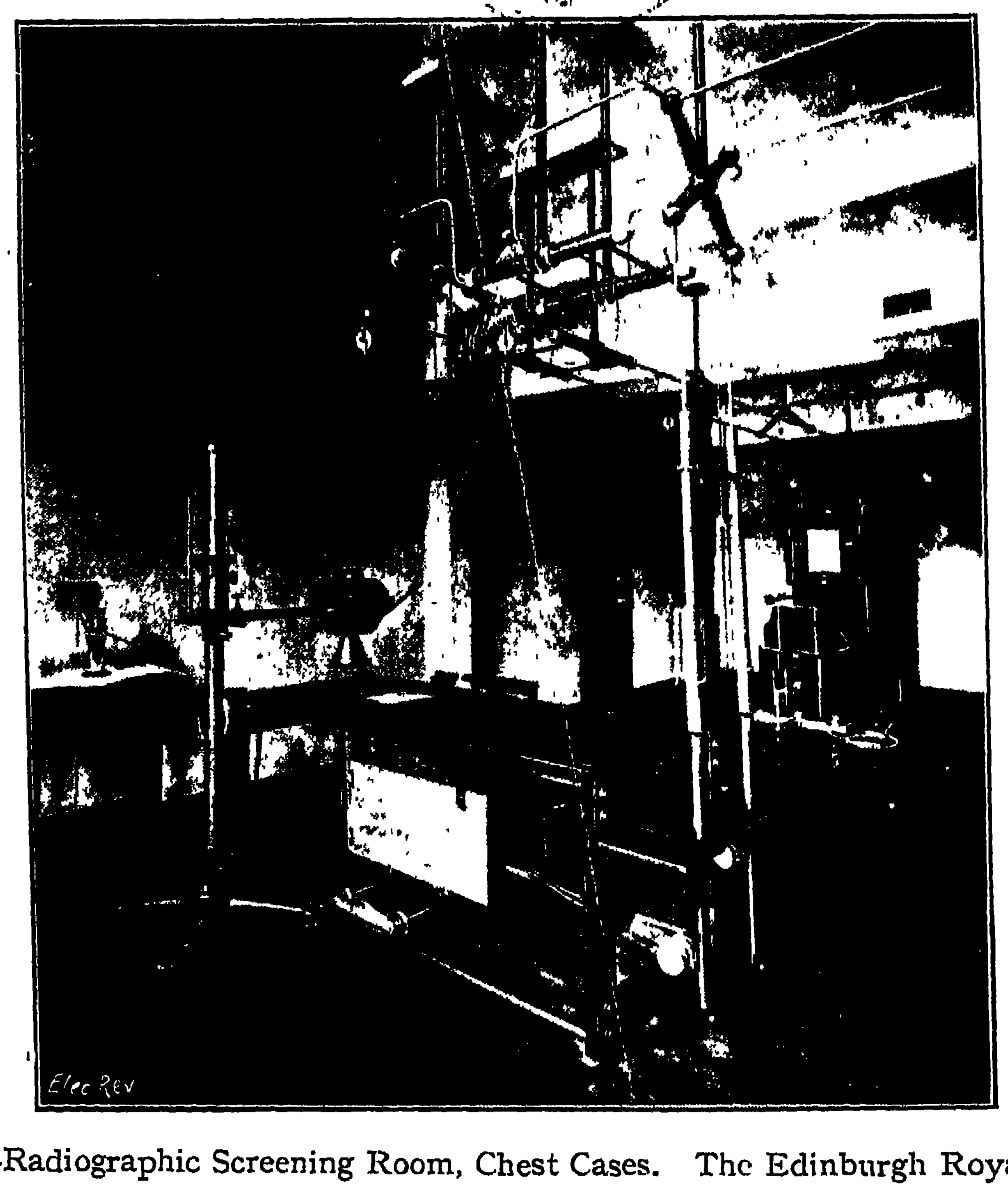



FIG. 490.—Radiographic Screening Room, Chest Cases. The Edinburgh Royal Infirmary.

*To face p.* 501.]

*The dark room* is fitted with the most modern photographic developing plant and plates may be passed in and out *viâ* light- and X-ray-proof apertures.

On the first floor are various *rooms for electrical treatment, massage, etc.* To permit of various currents being obtained at all convenient locations, namely, 230-volt direct current from the town supply, 200-volt, 50-cycle alternating current from the machine room and low-voltage direct current from the accumulator batteries, non-interchangeable plug sockets are fitted throughout this floor. There is a *room for remedial and gymnastic apparatus*, with separate rooms for electrical treatments of male and female patients, in which Schnee baths, diathermy, high-frequency and similar treatments are given. Two *ultra-violet light rooms*, one for males and one for females, are equipped with double carbon arcs. Throughout the department forced ventilation is obtained by means of air ducts and electric suction fans. Heating is provided by a steam radiator system common to the whole hospital. The cost of the installation was £52,000, and the equipment was entrusted to Messrs. Watsons & Sons, Ltd.

## THE RADIOLOGICAL BUILDINGS OF THE ST. JACOB HOSPITAL, LEIPZIG UNIVERSITY

Leipzig University Hospital claims to be one of the earliest hospitals to install X-ray apparatus, the original equipment being installed in February, 1896, by Professor Trendelenburg, immediately after Röntgen's discovery. This consisted of a small induction coil with a mercury interruptor installed in a cellar.

The equipment has been from time to time changed by the various radiologists, whom include the well-known therapeutic radiologists, Perthes and Heineke.

The installation was, in 1923, entirely reconstructed. The radiological work of the St. Jacob Hospital of the University is now carried out by two radiological institutes, one of which is devoted to medical work and the other to surgical work. Both are equipped by Koch & Sterzel.*

It is claimed that this institute is the largest of its type in Germany and doubtless in the whole World. The hospital's equipment was installed, not only with regard to the power of the apparatus, but also with great care as to the hygienic arrangements, and particularly with regard to the protection of the operators against X-radiation and the effects of poisonous nitric oxides and ozone.

It will be noted that two separate installations are present, one for the medical section of the hospital and one for the surgical section. Such a division is frequent in Germany, where the common radiological department often does not exist and the medical, surgical, dental, anatomical

* The author is indebted to Messrs. Koch & Sterzel for the loan of blocks of this installation.

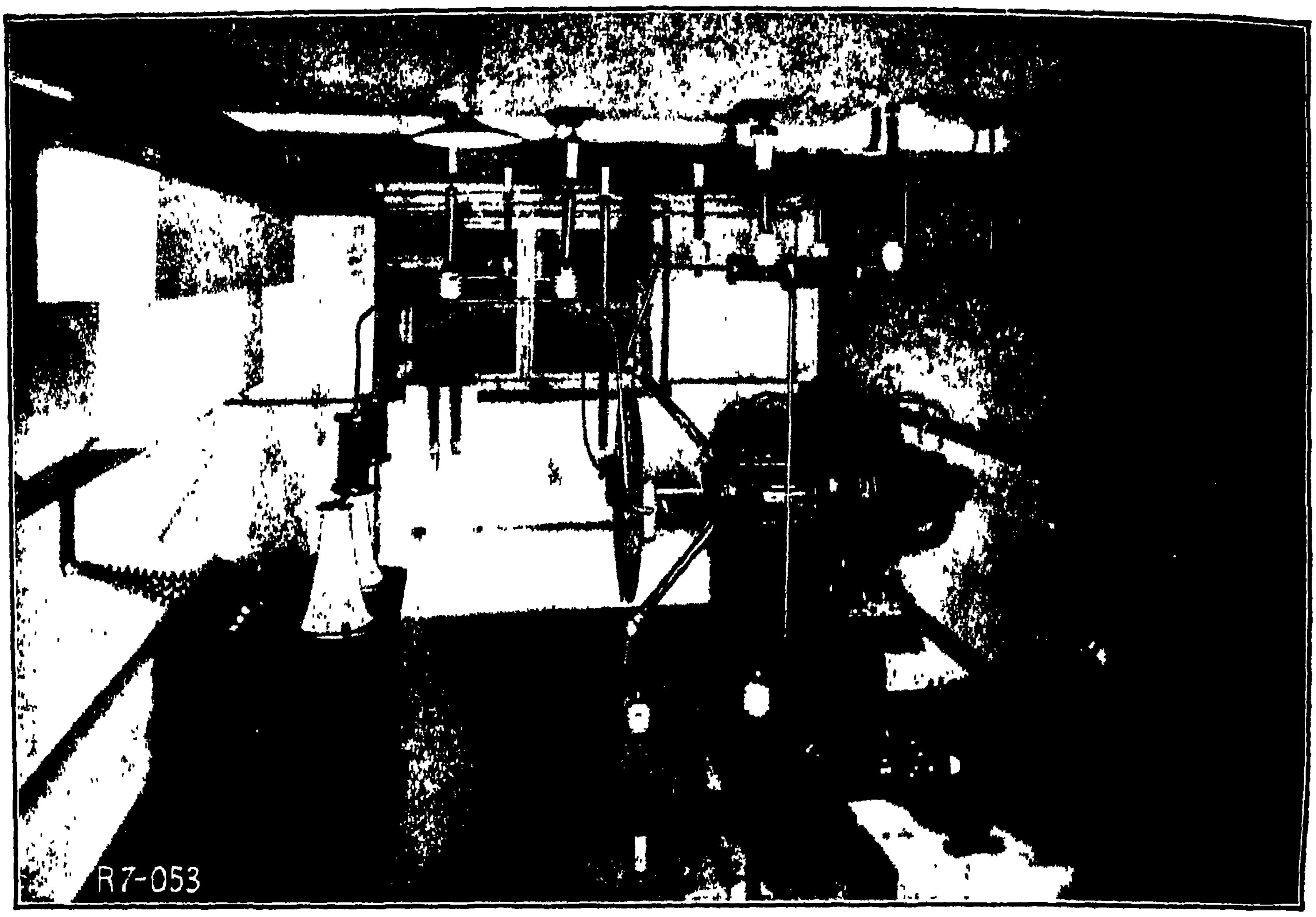



FIG. 492.—Machine Room. The Medical X-Ray Department, Leipzig University.

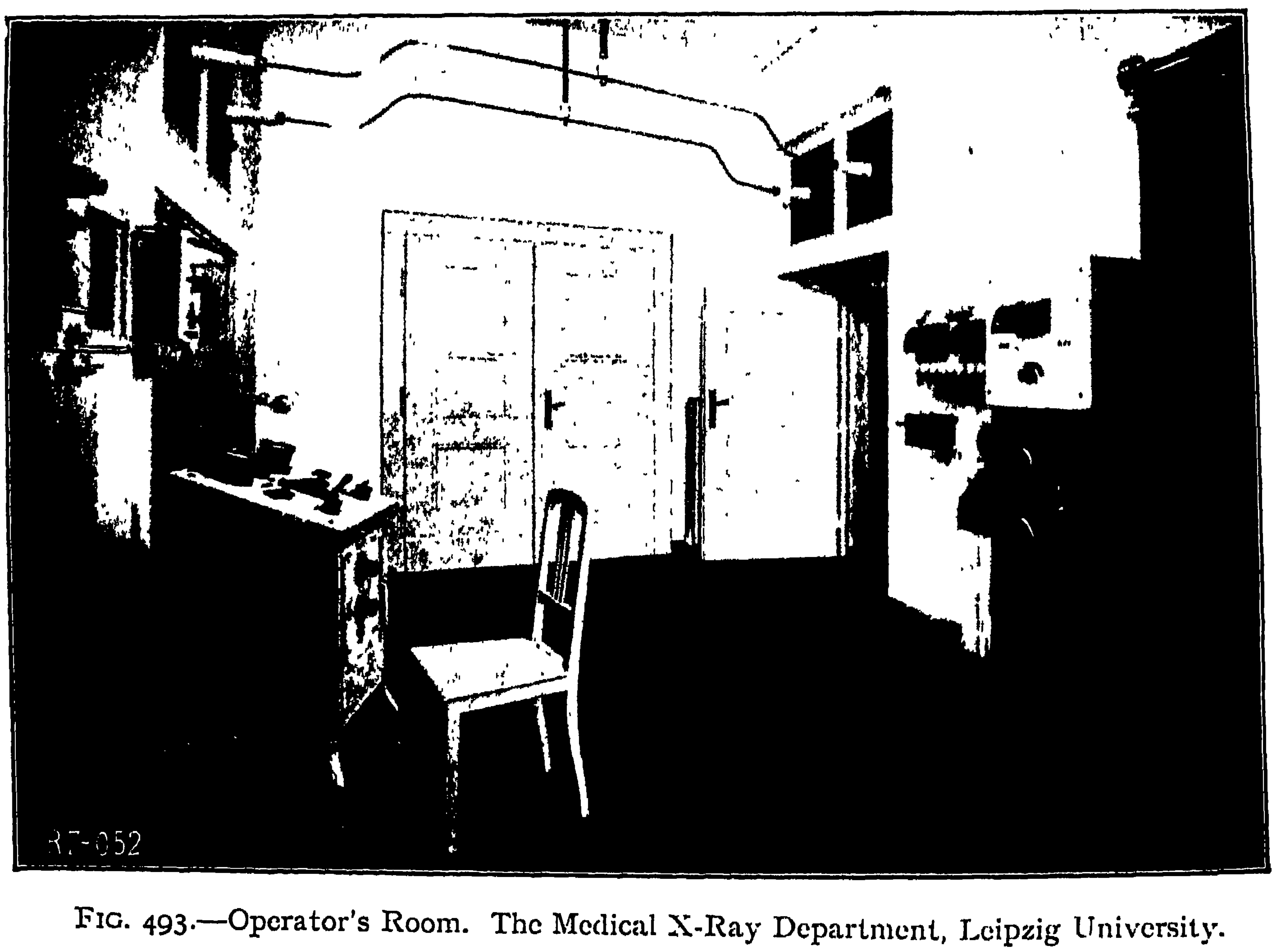


FIG. 493.—Operator's Room. The Medical X-Ray Department, Leipzig University.

*The Medical Department.*—This is shown in Fig. 491, and comprises two treatment rooms 1 and 2, both under control from an operator's room 3, adjacent to which is an ante-room for patients 4, and an assistant medical officers' room 5. Entrance from the hospital is obtained by a connecting corridor 14. The diagnostic work is carried out in a large room 7, having a protective cabin 6, and with its own waiting room 12, lighted by a courtyard 13. Arrangements are made to pass directly plates from the radioscopic room 7 to the dark room 11, and to receive stretcher cases by means of a lift 10, opening upon a landing 9. The senior radiologist has his own room at 8.

The high-tension apparatus (Fig. 492) is situated in a cellar beneath this floor and consists of a large direct-current/alternating-current rotary converter "Radio-Transverter" apparatus, with connected rectifying disc, and a smaller machine to supply the filament circuits of the electron type tubes. This cellar is ventilated by a large air shaft with forced draught seen passing through the left-hand upper window, and maintained at a constant temperature by steam pipes. The high-tension current from the oil-immersed transformer with protective choke coils, to the left, after rectification at the rectifier disc, passes to the floor above by means of a large shaft. Further protective anti-surge coils are placed in the leads.

The operator's control room is seen in Fig. 493, where the high-tension leads pass to the left *viâ* insulator panels, to the therapy rooms, and to the right, to the diagnostic room. The door in the centre opens into the ante-room 4, and that to the right opens into the protective cabin of the diagnostic room.

The switch-board and starting panels of the machines in the cellar below are seen to the right, and the actual operation of the X-ray circuits proper is controlled by the trolley switchboard to the left. The general spaciousness of this control-room should be noted. All the walls are of protective cement and the doors are covered by 4-mm. lead sheet beneath the woodwork.

The two treatment rooms (Fig. 494) are separated by a low protective wall. Forced removal of nitric oxides and ozone is arranged by ventilators, one of which is seen in the right-hand lower corner. The filament transformers for the electron tubes are suspended from the ceiling and the milliamperemeters are similarly mounted, so giving a clear view of the controlling instruments *viâ* the windows of the control-room.

Radiation is applied to the patient by means of a tube stand. Since, in Germany X-radiation is considered as equivalent to a definitely poisonous drug, which only has therapeutic effects when given with correct dosage, the measurement of the dosage of X-radiation is of utmost importance and this is provided by the Wulf ionoquantimeter, with flexibly connected ionisation chamber, seen in the foreground.

The protective cement operator's cabin of the diagnostic room is seen

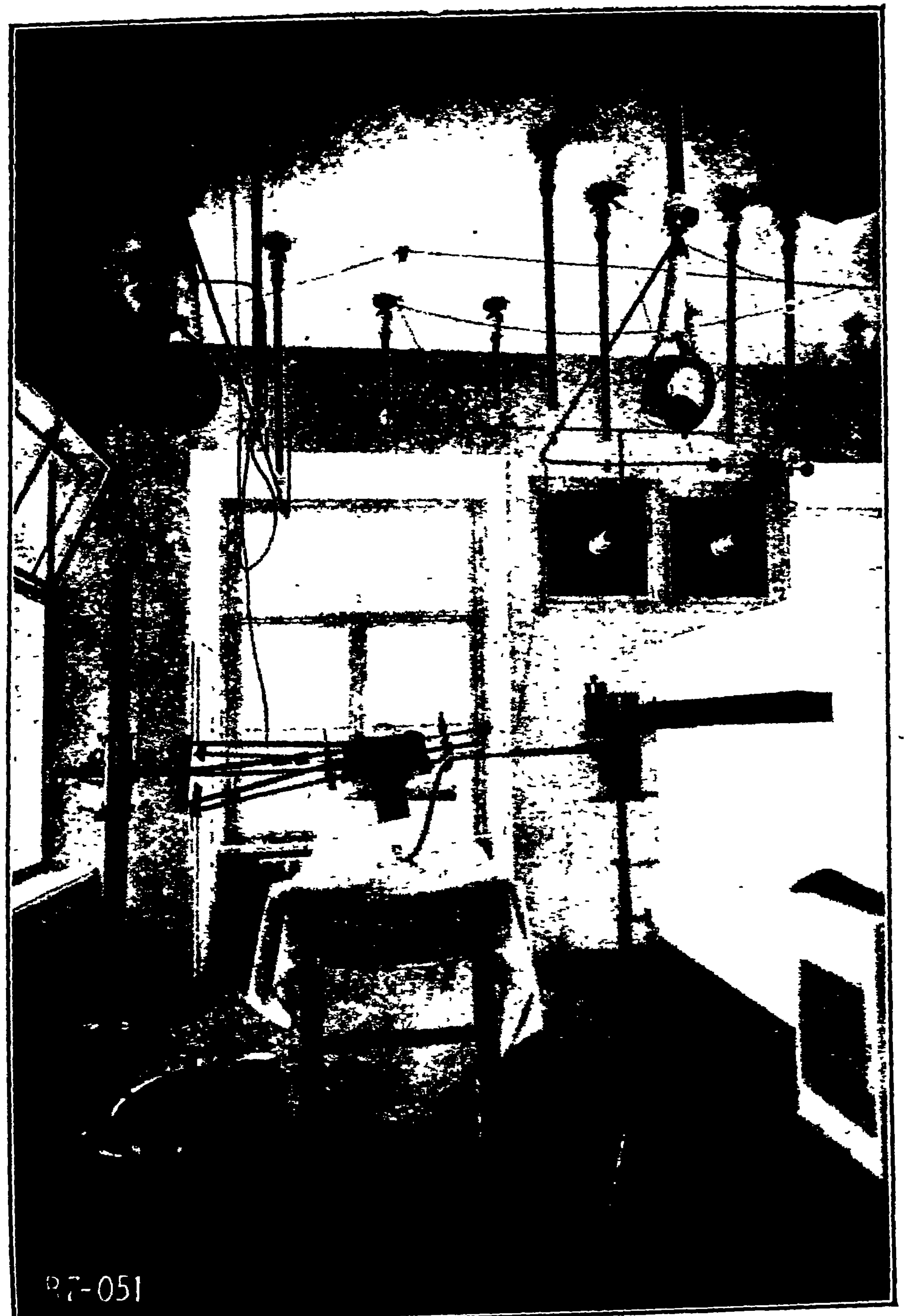


FIG. 494.—Treatment Room. The Medical X-ray Department, Leipzig University.

FIG. 495.—Protected Cabin for Operators. The Medical X-ray Department, Leipzig University.

To face p. 505.]

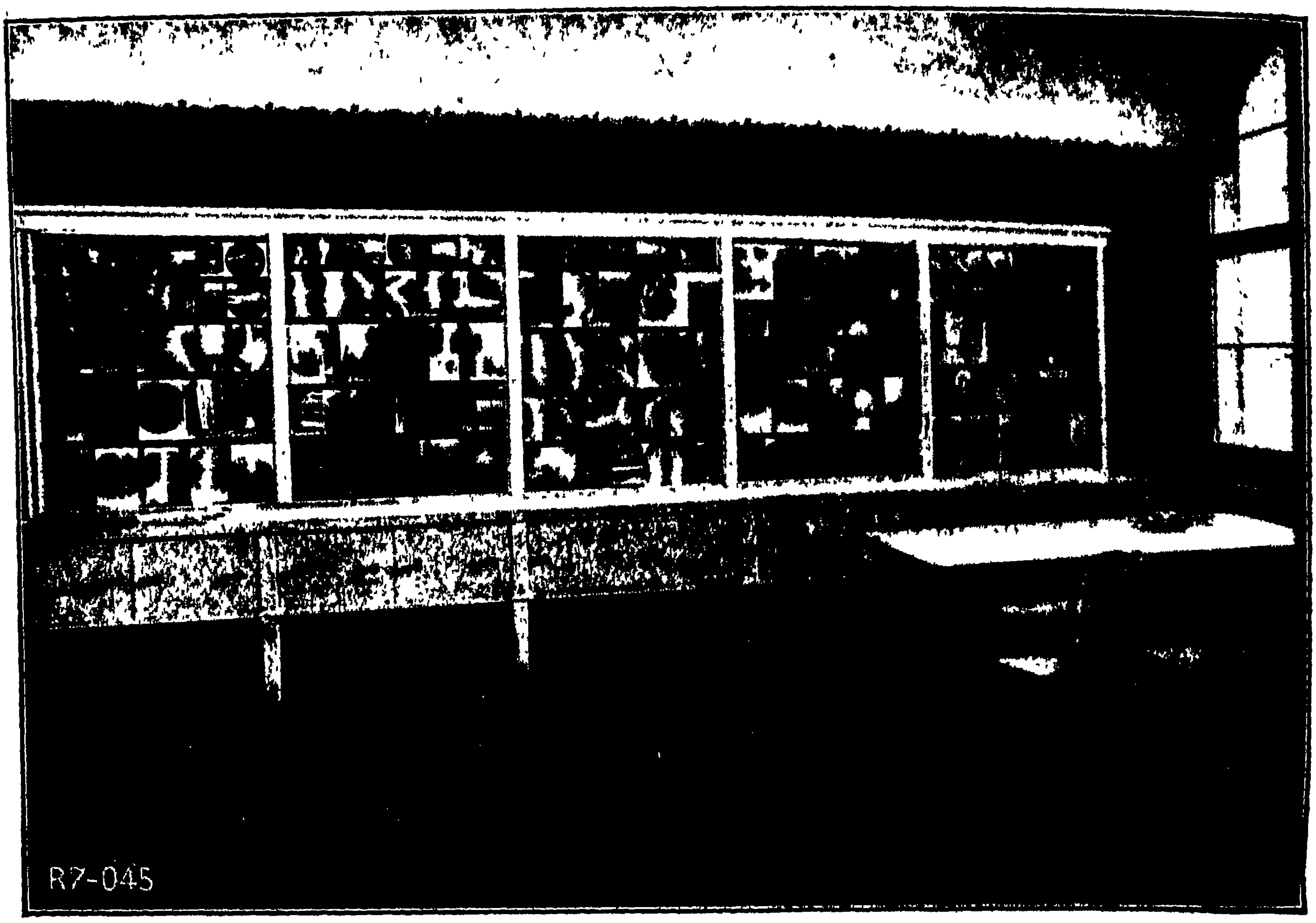



FIG. 497.—Viewing Cases. The Surgical X-ray Department, Leipzig University.


FIG. 498.—Radioscopic Room. The Surgical X-ray Department, Leipzig University.

*To face p.* 505.]

*The Surgical Department.*—This is claimed to be the largest therapeutic clinic in Germany and possibly in the World. It consists of two floors, the ground floor being devoted to diagnostic work only, and the first floor purely to therapeutic work. The general layout of the two floors is shown in Fig. 496. The general construction is with Kampe-Lorey barium cement.

The ground floor comprises a long corridor, from which the various rooms open. The first room is devoted to the centralisation of the various power switchboards, meters, etc.

Next to this room is a waiting-room for walking patients, and a second waiting-room for stretcher cases, which is directly opposite a lift serving the various floors.

Near this is a room in which plates are stored, and the previous day's plates are exposed to view in large viewing cases (Fig. 497), which is conveniently adjacent to the senior radiologist's private room when points arise for discussion. The layout of this floor is so designed that there is no need for non-radiological persons to enter the actual working rooms in order to obtain plates, to see the radiologist, etc.

Patients to be examined are brought to a waiting and dressing room, which by a series of traps gives direct entry into the radioscopic room (Fig. 498). This room should be particularly noticed as illustrating the ideal radioscopy room, *i.e.*, a large well-lighted and airy room, in which the apparatus occupies only a small proportion of the floor space, leaving ample space for movement in the dark, without fear of injury by walking into apparatus. A protective cabin for the control apparatus is seen to the left and the means of excluding light when working are obvious.

A radiographic room is separated from the above room by an operator's room, conveniently situated to both these working rooms. This radiographic room (Fig. 499) is again a well-lighted room, and has a protective screen (seen behind the tube stand), behind which are situated apparatus controls.

The remaining rooms of this floor are the dark room, a film-drying room and a special kitchen, in which barium meals are prepared more safely and hygienically, than, as is usual, in the X-ray room itself.

The therapeutic floor has a similar large corridor (Fig. 500), served directly by the lift. From this corridor all the rooms open. Numerous cupboards in this corridor serve to store the patients' plates, etc.

The central part of this floor is occupied by the therapeutic rooms, which comprised a long gallery, in which the generating plant is installed, a middle system of seven treatment cubicles and a further long operator's corridor, from which the cubicles are kept under observation. Entrance to the cubicles is obtained from this corridor *viâ* vestibules at each end.

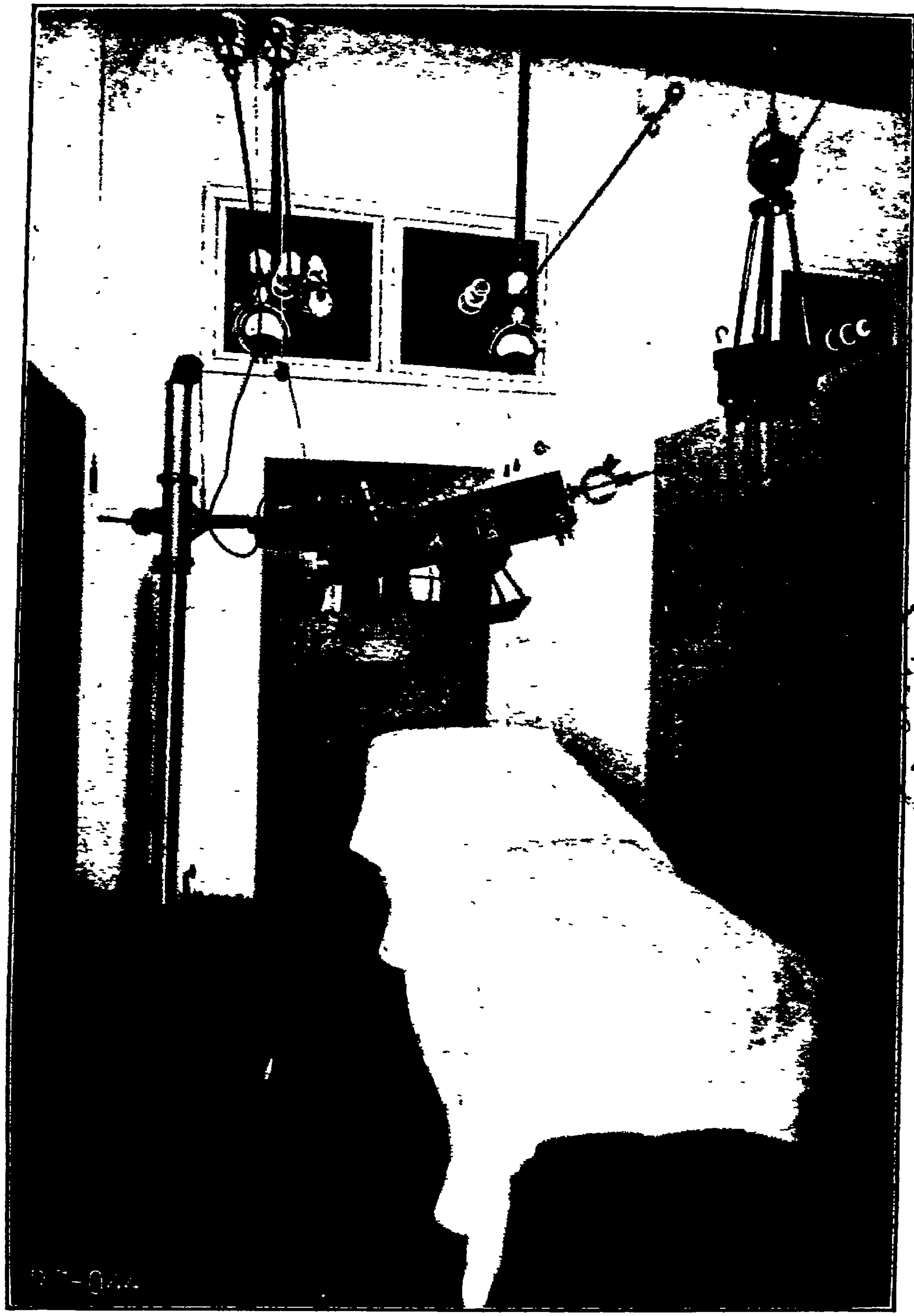


FIG. 503.—Treatment Cubicle. The Surgical X-ray Department, Leipzig University.


FIG. 504.—Operators' Corridor. The Surgical X-ray Department, Leipzig University.

To face p. 507.]

## THE RADIOLOGICAL DEPARTMENT OF THE CITY HOSPITAL, ST. LOUIS, U.S.A.* (Dr. L. R. SANTÉ, M.D., F.A.C.P., F.R.C.R.)

In 1923, in consequence of the continued increase of radiological work, it was proposed to build and equip a new radiological department in the City Hospital, St. Louis, a hospital of 1,000 beds and a still more extensive out-patient clinic.

A systematic investigation of the features of all other American X-ray departments was made before commencing the erection and

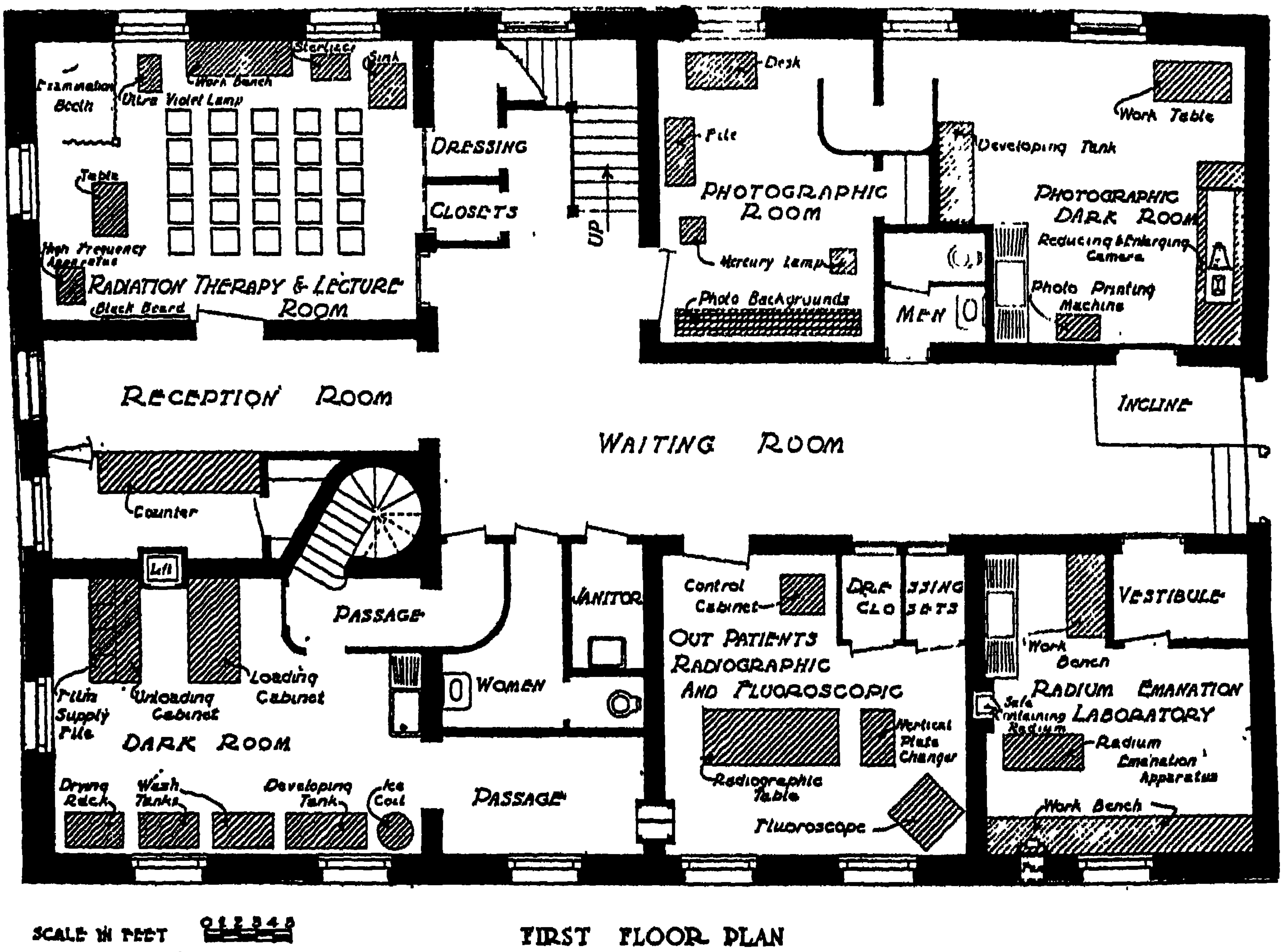



FIG. 505.—The City Hospital, St. Louis.

equipment, which was completed by May 1st, 1924. The equipment alone is valued at £20,000.

A separate three storey building known as The Radiological Building, is utilised solely for X-ray and radium work. This contains no less than twenty-two rooms with nine separate X-ray transformers. The ground floor opens upon the street and so allows direct entrance of out-patients, whilst all the floors connect directly with the hospital building.

On *the ground floor* (Fig. 505) is the photographic department, the

* The author wishes to express particularly his gratitude for the extreme kindness and courtesy shown to him by Dr. Santé in the supply of information and a large number of most excellent photographs of this very conspicuous X-ray institute.

floor, which it serves through a pass box. It is equipped with 11 ft. of stone developing and washing tanks, all provided with water of uniform temperature by means of a thermostatic control. Specially constructed cabinets are provided for loading and unloading and drying films. No less than 40,000 to 45,000 films are taken per year. One of the special features of the dark room is its equipment with ventilating window sashes, as seen in Fig. 512. These are of galvanised iron construction and operate in a second window casement which fits over the original window frame. They consist of two opaque sashes, the upper (merely a flat sheet of iron) serving only to exclude light and remaining permanently in place, the lower constructed of interlocking C-shaped columns of sheet iron, which permit the ready passage of air but excludes the light. When ventilation is desired the outer window sash is raised before the darkening sash is closed. When ventilation is not desired, both the outer and the inner sashes are closed, the inner sash in this case acting merely to exclude the light.

*The out-patient radiology room* is used for examination purposes, and for medium voltage therapy, such as whooping cough and tonsil work. A pass box between this room and the X-ray dark room permits the passage of films, but also insures against the passage of light, by a self-locking handle, which does not permit the simultaneous opening of both the X-ray room and dark room doors.

*The radium emanation room* is equipped with the latest type of Debierne-Duane-Failla emanation apparatus, employing no unusual features with the exception that all movable parts, stop cocks, etc. are solidly supported by the metal frame work and an attachment, permitting an interchange between the two sides, allows independent pumping of either side of the apparatus. Five hundred milligrams of radium are in solution and 45 mgrms. are in plate and standard tubes.

*The second floor* (Fig. 506), except for a small radium measuring room, is given over entirely to X-ray and administrative work. The three main X-ray rooms are located across the end of the corridor. The radiographic room is directly above the X-ray dark room on the first floor and is supplied from it by means of a lift. It is equipped with a radiographic and a Bucky diaphragm table.

Throughout the entire department all overhead high tension aerials have been eliminated as far as possible. This has been accomplished by putting all high tension apparatus and conductors on the third floor (Fig. 507), and the aerial conductors merely come directly downwards through the ceiling wherever high tension terminals are required for the operation of X-ray apparatus, as is evident from Figs. 508, 509 and 512. All high-tension terminals switches are on the third floor and are operated by ropes running through conduits in the walls and emerging through a wall plate, conveniently located in respect to the X-ray control cabinet, one

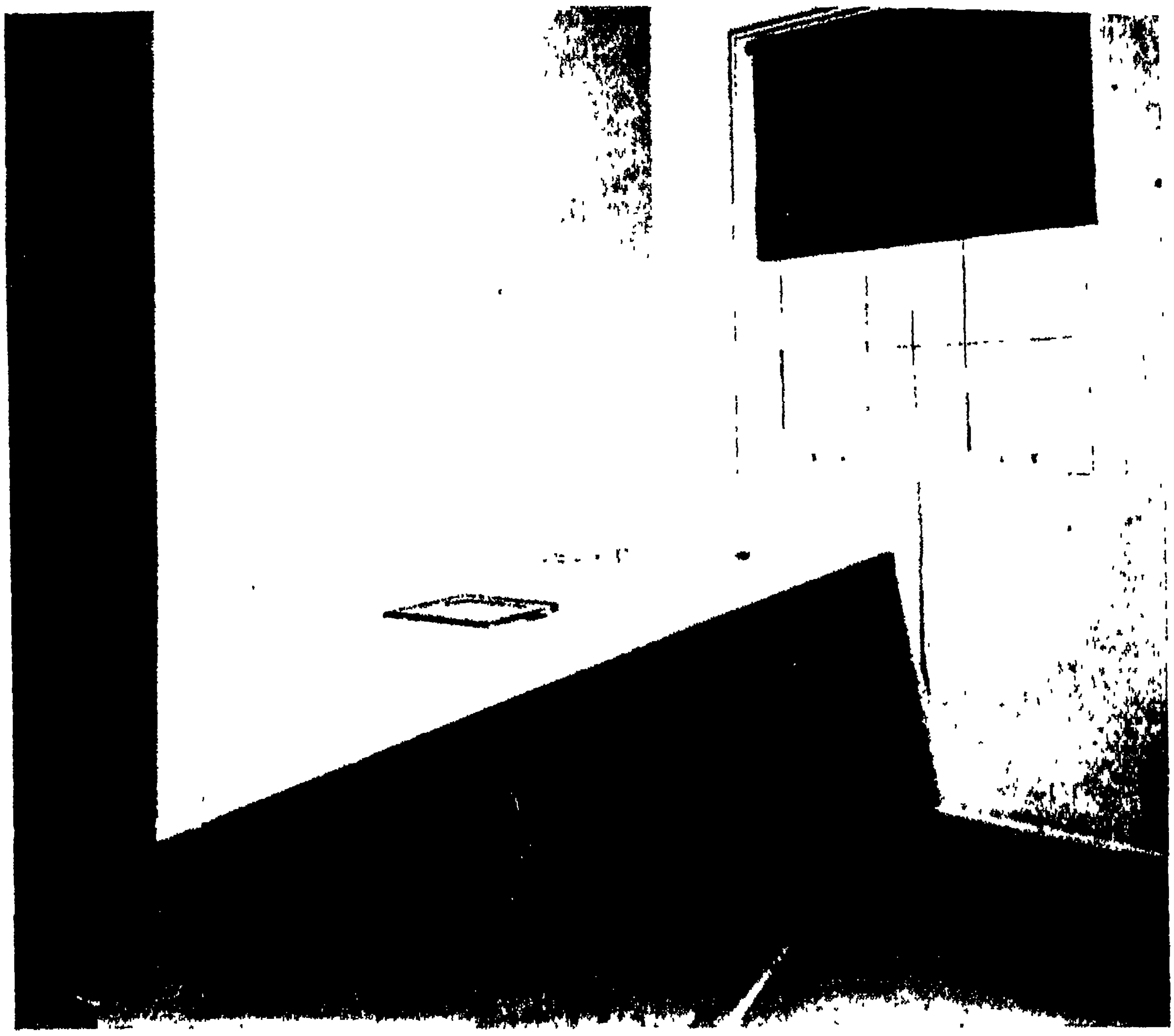


FIG. 510.—Treatment Cubicle for Vertically-directed Irradiation. The City Hospital, St. Louis.

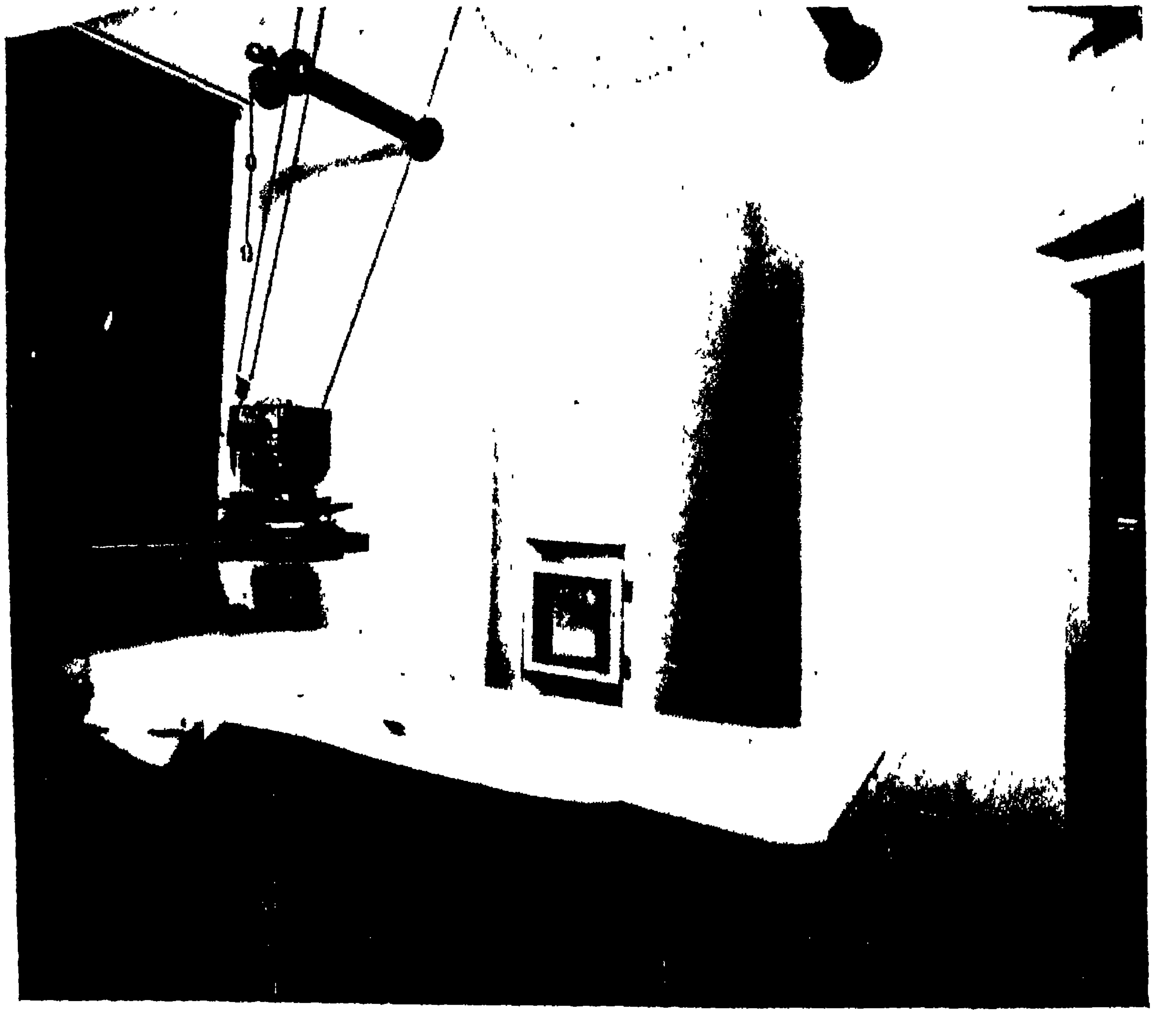


FIG. 511.—Treatment Cubicle for Horizontally-directed Irradiation. The City Hospital, St. Louis.

*To face p.* 511 ]

high tension terminals, but is rarely required. In both compartments the ports are provided with ionisation chambers, *viâ* which the rays pass to the patient, which give a continuous reading upon the control table located in the corridor (Fig. 506). Both tables are provided with push buttons to permit the patient to attract the operator's attention in case of necessity.

The construction of these compartments is entirely of metal lath and barium sulphate plaster. The grounded metal lathing forms a cage around the high tension apparatus and so gives complete electrical protection to the patient. The barium plaster walls give protection against X-radiation both to the operator and the patient. Dr. Santé considers that ordinary sand is of little value in stopping X-rays but, when barium sand is used, the result is most gratifying. Two and a half inches of barium plaster made of equal parts of barium sand, barium sulphate, Portland cement, and applied in eight or ten coats, is equivalent to over ·25 in. (6·35 mm.) of lead for 200 kv. X-radiation, or radium gamma radiation. Here, as elsewhere in the department, the transformer, motor and the tube water-cooling system is upon the floor above.

On the second floor is also the emergency radiographic room, the cystoscopic room, the fracture and the esophagoscopic room. Being a free general hospital a large amount of accidental emergency work is dealt with. Such work can be carried out throughout the whole day and night by three shifts of operators, each of eight hours' duration.

*A special fracture room* is provided with arrangements to permit reduction of fractures under the screen. The equipment is notable in that two separate transformer apparatuses (Fig. 512) allow vertical and horizontal fluoroscopic work, and so allow two views at right angles. These units are notable in that the X-ray transformers and the X-ray tubes are in oil immersed boxes, one box for each direction of radiation (Fig. 512). Hence external high-tension conductors, with consequent danger, are entirely eliminated, except for terminals for use of emergency apparatus on the floor above.

The top of the table is false and can be removed from under the patient to permit the convenient application of plasters. This table also serves for the bronchoscopic removal of foreign bodies under the fluoroscope.

*The cystoscopic room* is equipped with a special cystoscopic X-ray table and the necessary irrigators, sterilisers, etc. for carrying on such work. The high tension transformer is on the floor above.

*The radiographic emergency room* is supplied by separate electrical mains so that, in case of failure of the normal supply, all urgent work could be carried on in this room.

The remainder of the rooms of this floor are for administrative purposes and consists of a *main office and film-viewing room*, the *staff consulting room*, and a *private office for the senior radiologist.*

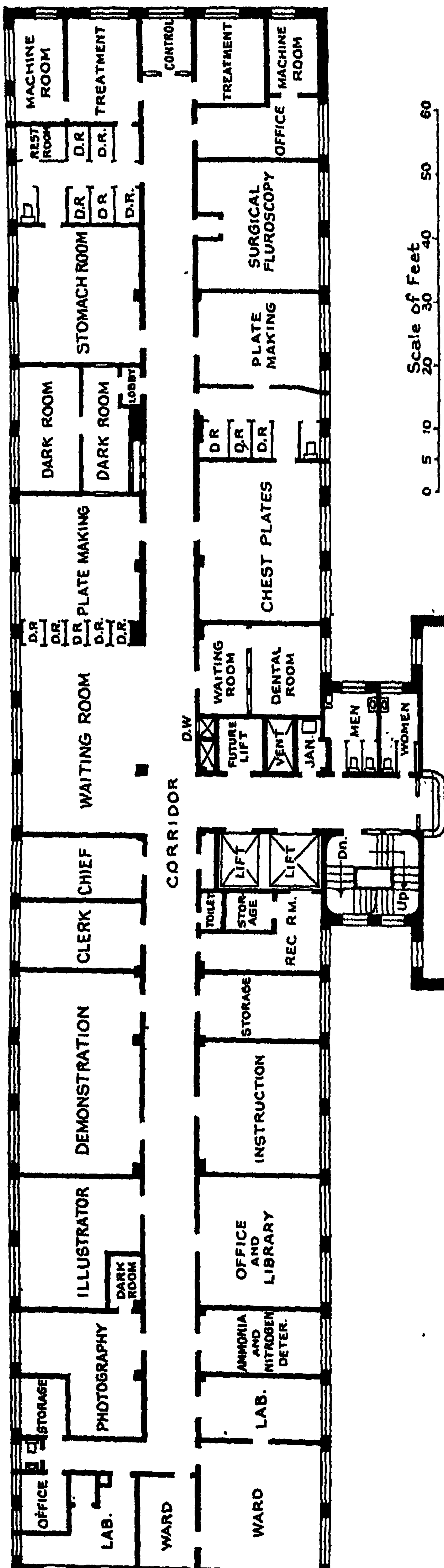



Fig. 513.—X-Ray Department. The University Hospital, Ann Arbor, Michigan, U.S.A.

The X-ray Department of this hospital (Fig. 513) is located on the second floor of the clinic wing, but is directly connected with the rest of the hospital by corridors and elevators, and comprises a floor area of 12,000 sq. ft. The commodious waiting-room directly connected with one of the main corridors of the hospital serves as a reception room for the admission and registration of patients referred for X-ray examination and treatment. The medical *personnel* of the department consists of the director (Dr. P. M. Hickey), the assistant director, four senior residents in Röntgenology and four junior residents in Röntgenology, all of whom are graduate physicians. The technical *personnel* consists of the dark-room technician, the registration clerk, the chief nurse in the diagnostic department, the chief nurse in the therapy department, the dental technician, four stenographers, a clerk for cross-indexing and filing, a clerk for filing films, ward helpers and orderlies. The department is self-sustaining, inasmuch as there is a separate charge made for the X-ray examination of county cases and also for those patients referred for consultation with the hospital staff. Patients are registered in the X-ray department upon presentation

FIG. 514.—Dressing Rooms. The University Hospital, Ann Arbor, Michigan.

FIG. 515.—Radiographic Room. The University Hospital, Ann Arbor, Michigan.

*To face p.* 515.]

dressing rooms and lavatory, so that the patients for thoracic examinations do not pass into the room where other examinations are going on.

*The thoracic room* is provided with a vertical fluoroscope and a separate X-ray machine for thoracic plates. On entering the thoracic room each patient is carefully examined fluoroscopically and a blank is provided which permits of a rapid summary of the important fluoroscopic findings. After the fluoroscopic examination the stereoscopic chest films are made at a target-film distance of 7 ft. (Fig. 516). Patients are usually examined in the erect position and are immobilised by a wide canvas band. The purpose of making the films with the tube at the distance of 7 ft. serves first, to minimise the distortion of their vertebræ, and second, to permit accurate cardiac measurements.

By having the patients fluoroscoped before films are made, the number of re-takes is markedly decreased. The films are all stereoscopic and are made during one respiratory pause; the exposure and kilovoltage vary according to the thickness of the chest. The patient is callipered in the antero-posterior diameter and a record of the same is made on the requisition blank. In this room is the table for pneumo-peritoneum studies, and here are made all the examinations of the chest, where iodised oil (lipiodol) is used for demonstration of the bronchial structure.

Adjacent to the dark room is the *gastro-intestinal department*, which department is also provided with its own dressing rooms, lavatory and rest room; the dressing rooms opening by a private corridor into the examination room; a separate door is provided for the entrance of stretcher cases. This room is provided with a vertical fluoroscope, a horizontal fluoroscope, and a serial plate table for serial plates of the stomach. All fluoroscopic notes are recorded on a special blank for this purpose, which permits of the rapid notation of the important parts in the fluoroscopic examination. The patient is first given a gum acacia barium mixture, which serves for œsophageal study and also for the demonstration of the rugæ of the stomach, which is done with the patient before the vertical fluoroscope. The fluoroscopic screen is also provided with an attachment which permits of the making of a limited number of films with the patient in the erect position. After the vertical examination the patient is then examined on the horizontal fluoroscope. This table is provided with an oil-immersed tube and transformer which absolutely prevents contact with the high-tension wires. The barium enemata are made on this table with the oil-immersed unit. After careful examination in the various positions, the patient is then transferred to the radiographic table, provided with an oil-immersed unit under the table, which permits of the accurate centring of the parts of the stomach desired to be recorded, and a tube above the table, connected with a separate transformer, for the making of rapid plates in serial succession. By this arrangement either four or twelve views of the stomach can be

original requisition and carbon copies of the former reports. There are two filing systems used—the active and permanent ; the active or recent files include the last thousand cases, the films of which are contained in fireproof steel drawers, with each set of films in a cardboard folder, arranged in serial numbers. There is a small file for the envelopes of these cases. The original requisition is attached by a clip to each folder and remains attached until the film is read. After the formal report has been dictated on the dictaphone the requisition goes to the transcribing clerk and is there attached to the carbon copy, which is filed in its own special envelope. The original copy of the report is then sent to the general record room, where it is distributed to the various departments. The overflow from the fireproof cabinet in the plate reading room is transferred to the permanent record room and the envelope is transferred to the large permanent files. Each formal report is coded according to the condition found, and this code is transferred to a separate cross-index file so that any group of pathological conditions, for example, sarcoma of the femur, can be found under the appropriate cross-index file. No attempt is made to cross-index the normal findings except on special examination, such as the injections of lipiodol and in the use of dyes in gall-bladder investigations.

The *plate reading room* (Fig. 518) is provided with a large illuminating box lighted by Cooper-Hewitt lights and two stereoscopes, one of which is provided with small Cooper-Hewitt lights. These stereoscopes have horizontal mirrors, as suggested by the late Dr. Van Zwaluwenberg, and permits of two examiners, one on each side of the table, remaining seated during the stereoscopic examination. This minimises the fatigue of the examiner, as the work can be done in a much more comfortable position than if he were standing up, as in the older type of stereoscope. The films are permanently kept in a fireproof room, not heated, and provided with outside ventilation.

There is a *class room* for meeting small classes of students ; this room is equipped with illuminating boxes and a stereoscope. There is also provided a *general staff room*, in which each member of the staff has his own desk. This room serves to house also the lantern-slide cabinet and an extra stereoscope.

The Department of Photography of the hospital is attached to the X-ray department, where patients and specimens are photographed either with standard cameras or by the cinematograph and the films permanently preserved. A lantern-slide camera is provided for the making of lantern slides.

The X-ray department itself will be a well-lighted and commodious department, specially built for the purpose and not, as is usually the case at present, a Cinderella department housed in some ill-ventilated cellar. The darkened walls and small windows of the older X-ray department are a thing of the past.

As regards importance, both in the purely medical and the surgical branches of modern medicine, the radiologist of to-day is in the first rank of the members of the team of specialists forming the modern hospital staff.

## EXERCISES ON CHAPTER X

(1) What are the chief dangers to be avoided in an X-ray department and how would you guard against them? (Soc. of Rad. Exam., June, 1925.)

(2) State what methods you would employ in laying out a new X-ray room. How would you ensure safety to the operator from electric shocks and the danger of chronic dermatitis? How would you ensure that the patient is safe from acute burns during a protracted examination of the alimentary tract? (Soc. of Rad. Exam., December, 1925.)

(3) Give the accommodation requirements of a large X-ray department, and suggest how you would modify these to equip a small cottage hospital.

(4) Discuss the construction and equipment of a diagnostic X-ray room.

(5) Contrast the relative advantages of lead sheet and barium sulphate for X-ray purposes.

(6) Discuss methods to permit of entry to a radioscopic room, whilst examinations are being conducted, without inconvenience to the radiologist.

(7) Describe and sketch an installation for X-ray diagnostic work.

(8) Describe a large therapeutic X-ray installation, including protective measures for patients and staff.

(9) Describe the advantages of placing the high-tension generating plant in a separate room, and discuss the relative advantages of installing this (*a*) on the same floor, (*b*) below, and (*c*) above the X-ray room.

(10) Discuss the advantages and disadvantages of the cubicle and semi-cubicle layouts for X-ray therapeutic installations.

(11) Compare the advantages and disadvantages of (*a*) the semi-cubicle system, (*b*) the use of large protected X-ray tube holders, as regards protection in an X-ray building.

(12) Describe the present-day trend of progress in radiological buildings.

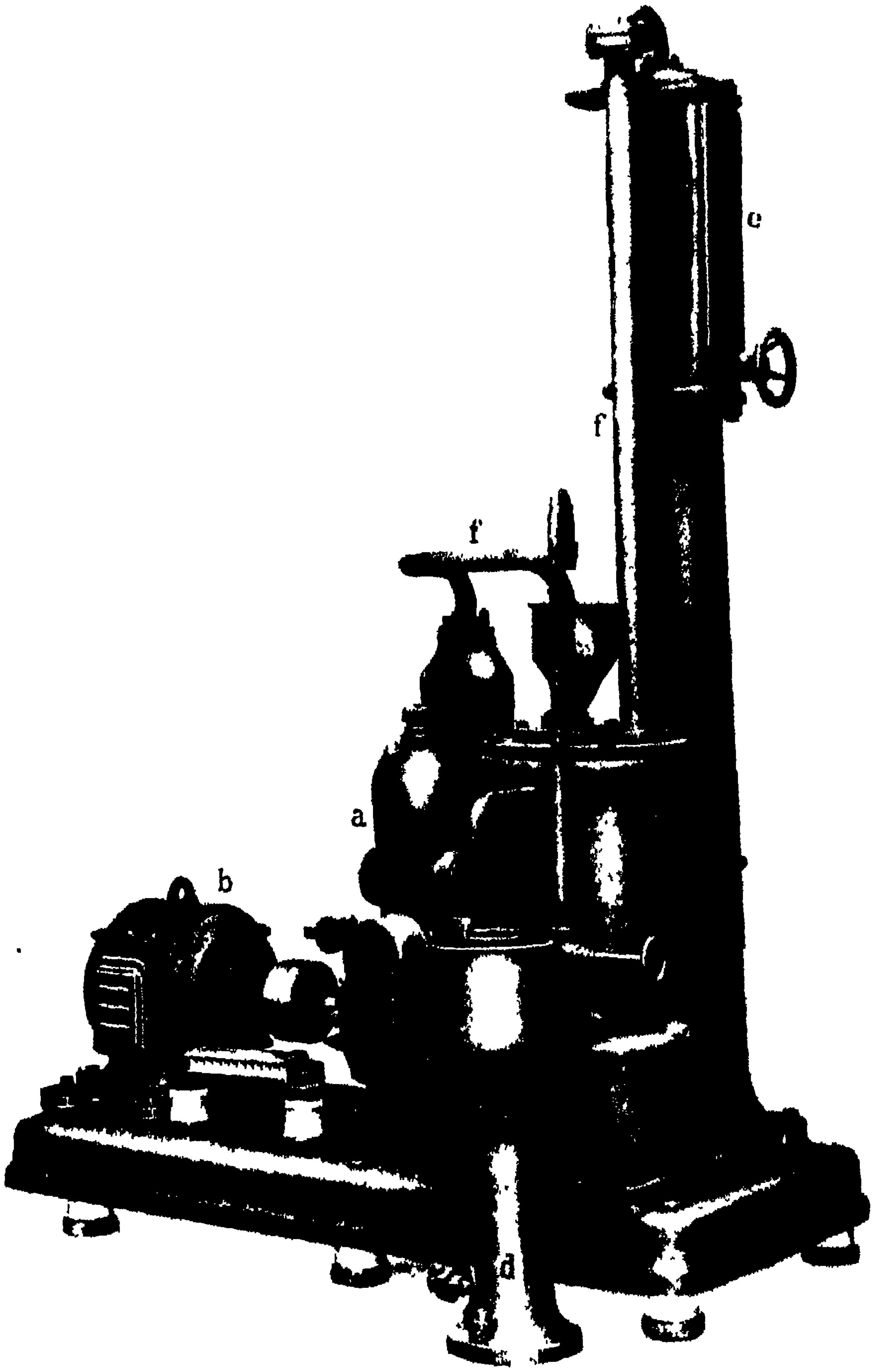



FIG. 519.—Brown-Boveri Oil and Mercury Vapour Pump. (*a*) Preliminary vacuum pump with automatic oil pressure governing. (*b*) Driving motor for preliminary vacuum pump. (*c*) High vacuum mercury pump, type GRH. (*d*) Circulating-water fittings with alarm for the high-vacuum pump. (*e*) Compression vacuum gauge, with hot-wire gauge mounted on the side. (*f*) Preliminary and high-vacuum piping.

*To face p.* 523.]

used as the medium in these pumps. The limit of the vacuum depends upon the vapour pressure and temperature of the sealing fluid and amounts to $2 \cdot 5 \times 10^{-2}$ to $1 \cdot 5 \times 10^{-2}$ mm. of mercury absolute, at a normal temperature of 20 C. This limiting vacuum can be strongly influenced by the partial pressure of water vapour, according to the moisture contained in the oil, so that under certain circumstances the preliminary vacuum produced may not be sufficient to ensure the proper working of the high-vacuum pump which runs in series with the preliminary pump. In order to exclude this as far as practically possible, the Brown-Boveri preliminary vacuum pump chiefly differs from the

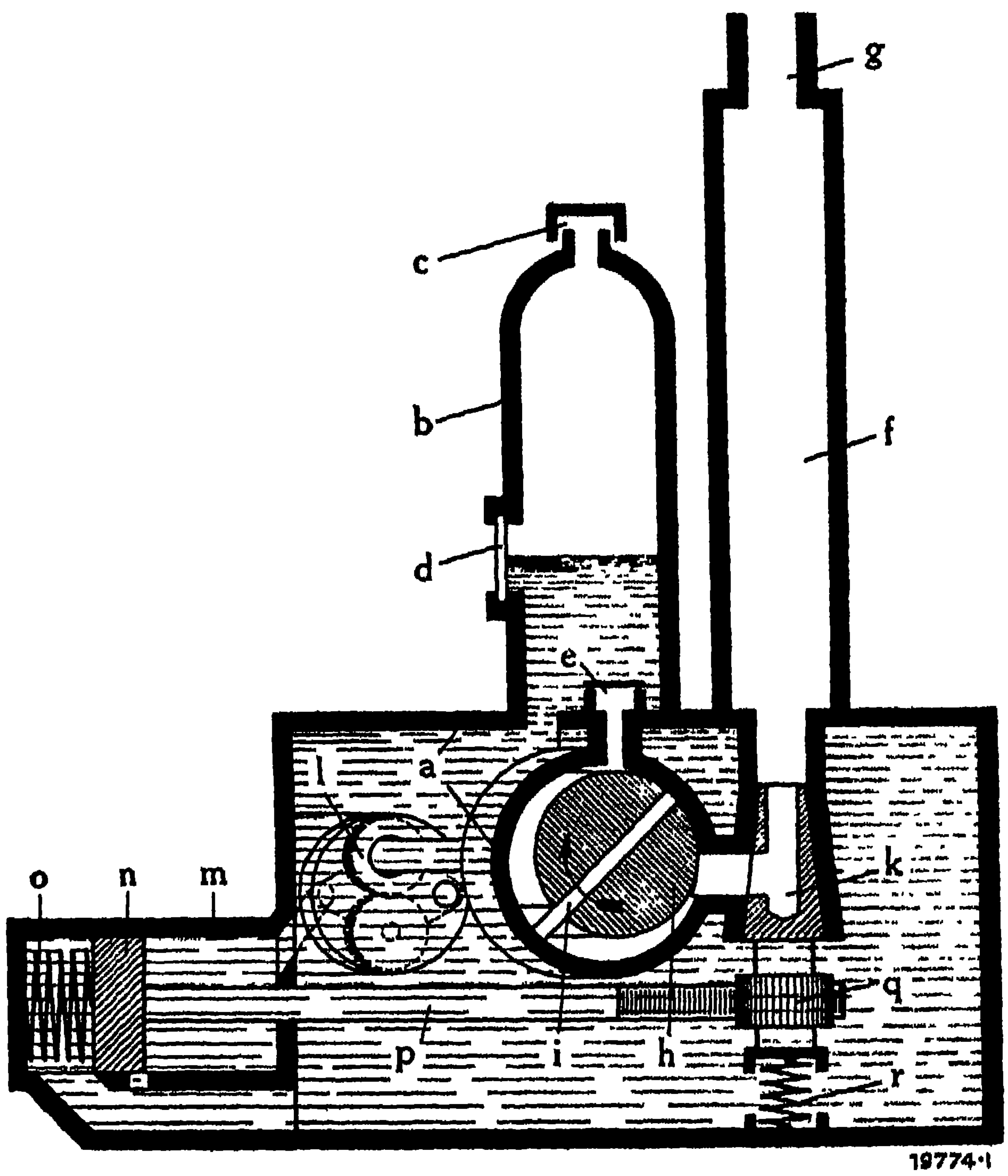



FIG. 520.—Diagrammatic View of Preliminary Vacuum Pump with Combined Oil-pressure Governor Gear Type. (*a*) Pump casing. (*b*) Exhaust dome. (*c*) Exhaust chimney. (*d*) Gauge glass. (*e*) Non-return valve. (*f*) Oil trap. (*g*) Preliminary vacuum pipe line. (*h*) Rotor. (*i*) Plate. (*k*) Rotary valve. (*l*) Geared oil pump. (*m*) Governing cylinder. (*n*) Piston. (*o*) Return spring. (*p*) Rack. (*q*) Pinion. (*r*) Compensating spring.

other existing designs in that the use of a vacuum sealing gland in the interior of the pump is avoided, so that the complete pump may be constructed as an *enclosed type*. The only point at which the oil is in direct connection with the atmosphere is at the chimney on top of the exhaust dome, so that the absorption of moisture is reduced to a minimum. Any moisture expelled from the apparatus collects on the bottom of the exhaust dome, and from there reaches the outer casing by means of a suitable opening. The water can do no damage in the outer casing, and, owing to its greater density, it collects at the bottom of the casing, whence it can be run off from time to time without interfering with the maintenance of the service. This type of pump, patented by Brown, Boveri & Co., also enables every inspection to be carried out in the simplest

sure drop is comparatively small and amounts to only about 0·2 mm. absolute of mercury. This pressure drop is sufficient to guarantee reliable working. The design is the simplest possible, as there are no internal fittings built on to the body. The working part consists of a cylindrical casting with a flat bottom which contains about 2 kg. of mercury. The high-vacuum piping is connected, at the side of the pump, to the cooling zone, while the preliminary vacuum piping is connected to the top of the casing. The working chamber, made from steel plate, is mounted in a cast-iron cylinder, the upper portion of which is designed to form a cooling chamber. The heating element, which is easily removable and consumes about 500 watts, is fitted in the base of the pump. All components can be easily removed and are accessible for control. As there are no separate parts inside the body the instructions provided enable the pump to be dismantled, inspected, and reassembled without special knowledge.

(4) *The circulating water fittings of the high-vacuum pump* vary according to the particulars of the installation and the method of cooling used. In the simplest cases a pedestal with the cooling water union, supply valve, and outlet funnel is mounted on the base-plate near to the high-vacuum pump. In the event of it being impossible to guarantee an uninterrupted supply of circulating water, a water-flow indicator as shown in Fig. 521, is used. This device is provided to avoid disturbances caused by the cessation of the cooling-water supply; a signal is actuated or a switch operated if the water supply is cut off. The heating element of the high-vacuum pump is immediately switched off in the event of a disturbance, thus preventing the mercury from entering the vacuum pipes. When the flow of cooling water recommences, the heating element is automatically switched in. The construction and method of operation of the water-flow indicator are as follows: A receiving vessel with an adjustable opening in the bottom is carried by one arm of a double lever; the second arm of the lever supports a balance weight. The outlet is adjusted so that the receiving vessel is kept filled by the smallest allowable flow of water, and overflows into the large funnel. In the event of an interruption in the water supply the receiving vessel empties and the balance weight is lowered. By this means a switch is actuated and the protective apparatus comes into operation. A water stop-valve is provided in unattended rectifier installations which use a continuous supply system for the cooling water, and also for plants in which water must be conserved (Fig. 522). The valve body contains a double beat valve which is operated by a no-volt coil; by this means the operating device is relieved from and made independent of the water pressure. A link motion attaches the core of the solenoid to the valve spindle, which passes through a gland before being secured to the valve disc. In order to overcome the friction in the gland effectively, the core is made very heavy and is connected to the link motion in such a way that it can fall freely through a certain distance both when opening or closing, thus giving a hammer blow which ensures positive operation. If the no-volt coil is energised, the core is drawn up and the valve opened. When the excitation is removed the heavy armature, which is connected by means of a link motion with a ratio of 1 ; 12, falls and thus positively closes the valve.

(5) *The Vacuum Gauge.*—The vacuum gauge, which constitutes a practical application of Boyle's Law for determining the pressure, was first suggested by MacLeod. At present it is the only practical instrument for the measurement of pressures of exceptionally low values. The method of operation is as follows: The gas, contained in the bulb connected with the rectifier by a capillary tube, is compressed into a capillary tube 1·5 to 2·0 mm. in

the upper end of the barometric tube. The cross section $f$ of the enlargement is made as large as possible, when compared with $f_1$, the annular section of the mercury container which is in contact with the air. By this arrangement, variations of the mercury column in the barometric tube due to atmospheric pressure or changes of temperature are compensated in a practical manner. The fluctuations are limited to the mercury container $f_1$ which is open to the atmosphere, and owing to the barometric height $h$, these have no effect on the measurements. In other words, for the correct setting of the mercury meniscus in the enlargement $a$, or in the barometric tube, the adjustment of the mercury container is independent of variations in atmospheric pressure and also of temperature changes of the surroundings, and hence the setting is always the same. From this it follows that the adjustment of the mercury meniscus in the barometric tube may be omitted, *i.e.*, it need not be visible.

The apparatus consists of an *iron tube* (barometric tube) on the upper portion of which an enlargement $a$, and a connecting branch $s$, are provided. The lower end of the mercury container $b$ forms a telescopic connection. The only glass portion necessary is the bulb $m$ with the capillary tube $k$, which is connected to the branch of the barometric tube at $q$ and sealed with mercury. In order to take a reading, the mercury container $b$ is raised to the fixed stop $d$ by means of the lifting device $c$. The position of this stop raises the mercury to the lowest altitude at which readings can be obtained. In this position (the measuring position), the mercury column in the capillary $k$ automatically adjusts itself to the correct height, determined by the instantaneous value of pressure, which can then be read directly on the scale in millimetres of mercury. After each reading the mercury container is lowered to its rest position, thus the apparatus is always ready for service. The scale and mercury column are illuminated to increase the accuracy of the reading.

The lifting device is fitted with an automatic friction brake, to prevent the container slipping as a result of careless attention. A special testing tube $p$, which is inserted instead of the bulb $m$ and capillary tube $k$, is provided for checking the adjustment of the mercury and determining the quantity of mercury. The testing tube enables the level of the mercury in the enlargement $a$ to be adjusted, sufficiently accurately for practical purposes, as soon as the instrument is placed under vacuum (about 0·1 mm. of mercury column absolute being ample) a previously defined mark being used as zero. Compensation for the meniscus in the capillary tube is obtained by increasing the height of the mercury level $f$ by an amount $y$. This adjustment is only necessary once and is carried out before the apparatus leaves the factory. The quantity of mercury may be subsequently checked by means of a float carrying suitable marks. The mercury necessary amounts to about 3·8 kg.

The improvements described thus enable the glass portions to be limited to the capillary tube and measuring bulb, the principal parts being made of metal. As the adjustment of the mercury in the barometer tube is no longer necessary before each measurement, a considerable technical advantage is attained. The attendance is extremely simple, special care and specialised knowledge are not required, since the mercury in the capillary tube automatically adjusts itself as soon as the container is raised to the stop $d$.

The principal disadvantage of the compression vacuum gauge is due to the fact that for every measurement the gas content of the bulb and capillary tube must first be sealed by mercury and then compressed in order to determine the vacuum present. This integrating method only enables the instantaneous value of the vacuum to be obtained; any fluctuations however are not given.

# APPENDIX II (CHAPTERS II AND III)

## RECENT DEVELOPMENTS IN X-RAY TUBE DESIGN

Dauvillier has suggested the use of an interruptor within a tube having a rotating target as described on p. 114. For example (Fig. 524), he proposed to interrupt the circuit of the inductance B and battery S (virtually an induction coil) by the contacts $S_1$ and $S_2$ within the tube, the latter having a rotating target operated by the internal rotor A and external stator M.

The same method could doubtless be applied to the alternating current rectifier disc. In this case it is quite possible the following advantages would result :—

(1) The large rectifier disc of the normal rectifier apparatus would be reduced to very small dimensions, particularly in the high-vacuum electronic tube, since sparking and arcing, in the absence of a source of electrons, would only allow passage of energy when the tube actually made contact, and small clearances would be sufficient to avoid sparking.

(2) Absence of the undesired noise of the rectifier disc. This would possibly assist greatly the choice between the cheaper normal disc rectification and the expensive noiseless valve tube rectification (p. 343) in favour of the former.

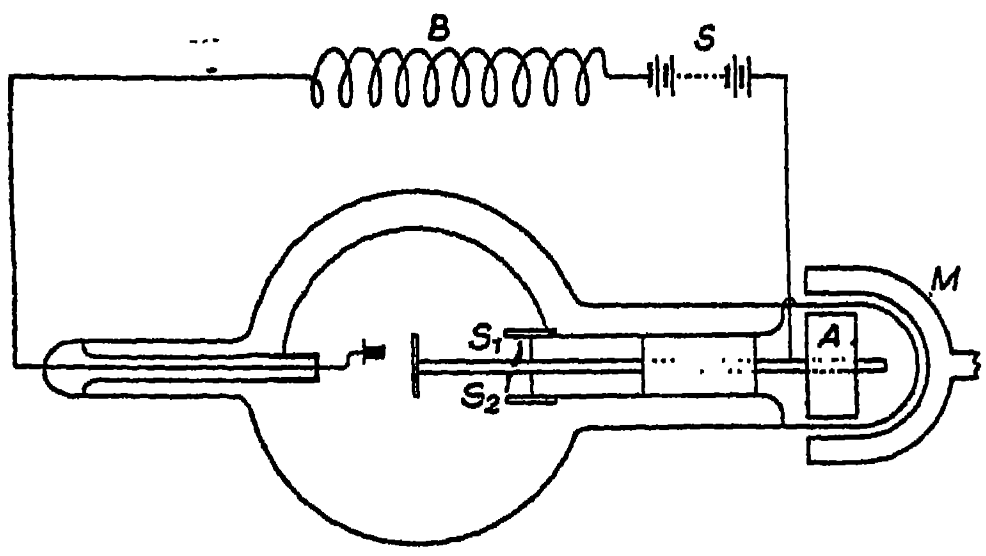



FIG. 524.—Dauvillier Tube with Vacuum Interruptor.

It appears remarkable that such an attempt to decrease the size of the normal rectifying disc and its noise, by enclosing it within a vacuum, has never yet been carried out. The practical difficulty, as with the above tube, is to maintain the vacuum in the presence of the rotor windings, in which air is present, but this has been successfully obtained in the Holweck pump (Fig. 13).

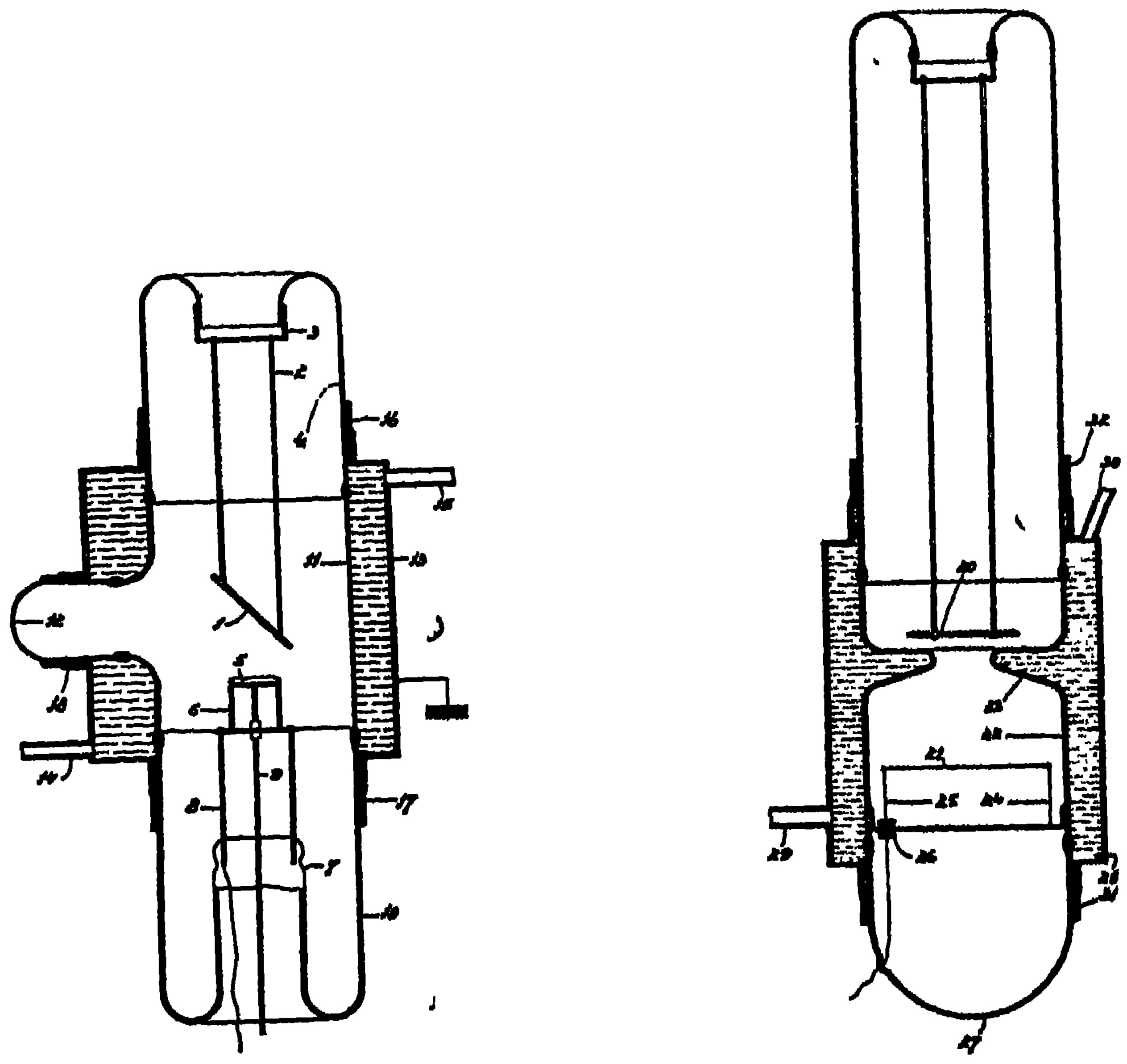
Philips (Brit. Prov. Patent 4,145/1927) have recently designed a new form of rotating target tube (Fig. 525), which the normal arrangement of the " Metallix " tube facilitates. In this a ball-bearing rotor 7, operated by an external stator 9, causes rotation of a target 3, receiving electrons from the eccentric filament 4 and emitting X-radiation from a window 12. This tube has not yet come into use. Doubtless the difficulties of exhaustion, mentioned above, are not so great in the gas-filled " Metallix " tube, as with the highly exhausted pure electron-discharge tube.

This is indicated by a further patent of this company (Brit. Patent 243,310/1924), in which an iris diaphragm 24 and 15 (Fig. 526) is actually inserted within the X-ray tube itself and operated mechanically, by the gears 33 and 34, under control of a magnetic mass 37.

Such an arrangement would have obvious advantages over the normal diaphragms exterior to the X-ray tube, since the great reduction in size would allow the nearer approach of the tube to the patient where this is desired.

windowed tubes are made. Filament and anodes are readily interchangeable, and anticathodes with targets of platinum, silver, tungsten and copper are supplied. With corresponding filters it is stated nearly monochromatic radiations can be obtained, as shown by the following table ;—

| Target. | Filter. | Line $K_{\alpha_2}$ (Å.). | Limit of absorption of the filter (in Å.) | Critical tension (Kilovolts). |
|---|---|---|---|---|
| Pt | Wo | 0·19 | 0·187 | 79 |
| Ag | Pd | 0·56 | 0·510 | 26 |
| Mo | Zr | 0·71 | 0·686 | 20 |
| Cu | Ni | 1·53 | 1·480 | 9 |



*a* *b*

FIG. 527.—Water-cooled Philips Tubes.

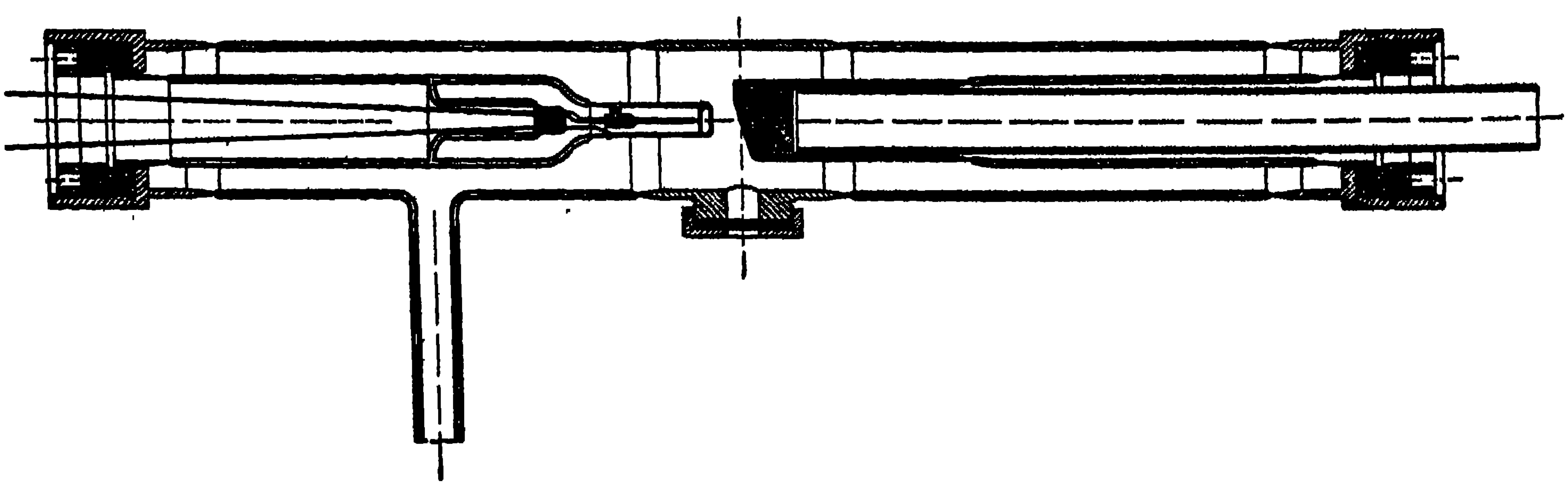


FIG. 528.—Experimental Philips Tube for Permanent Connection to the High-vacuum Pump.

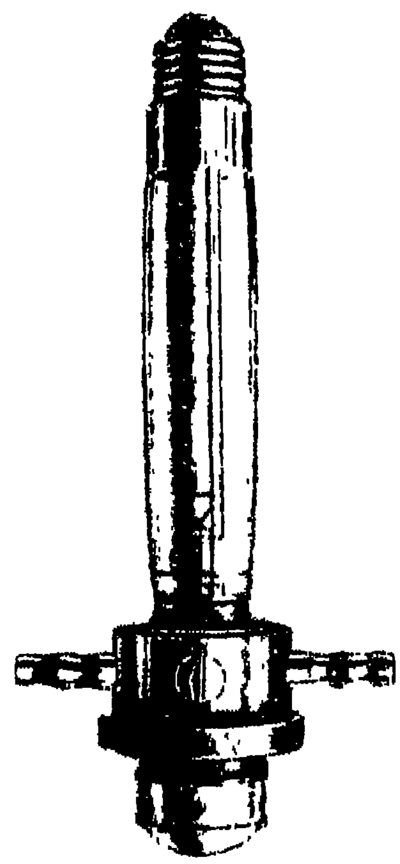


Fig. 529.—Bucky Soft Radiation Tube (Messrs. Müller).

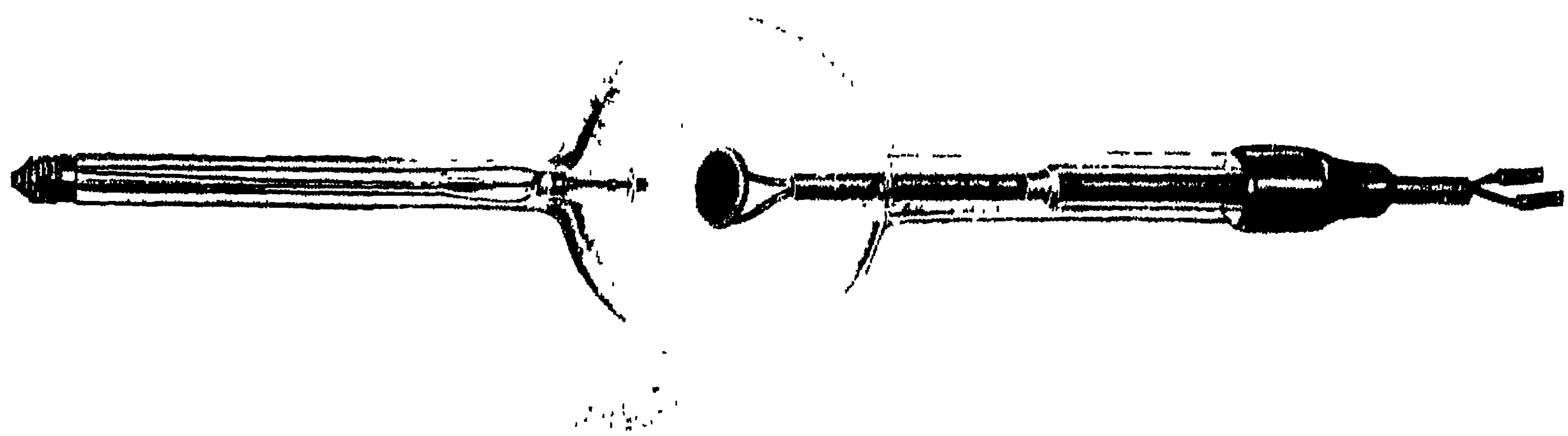


Fig. 531.—Water-cooled Deep Therapy Coolidge Tube.

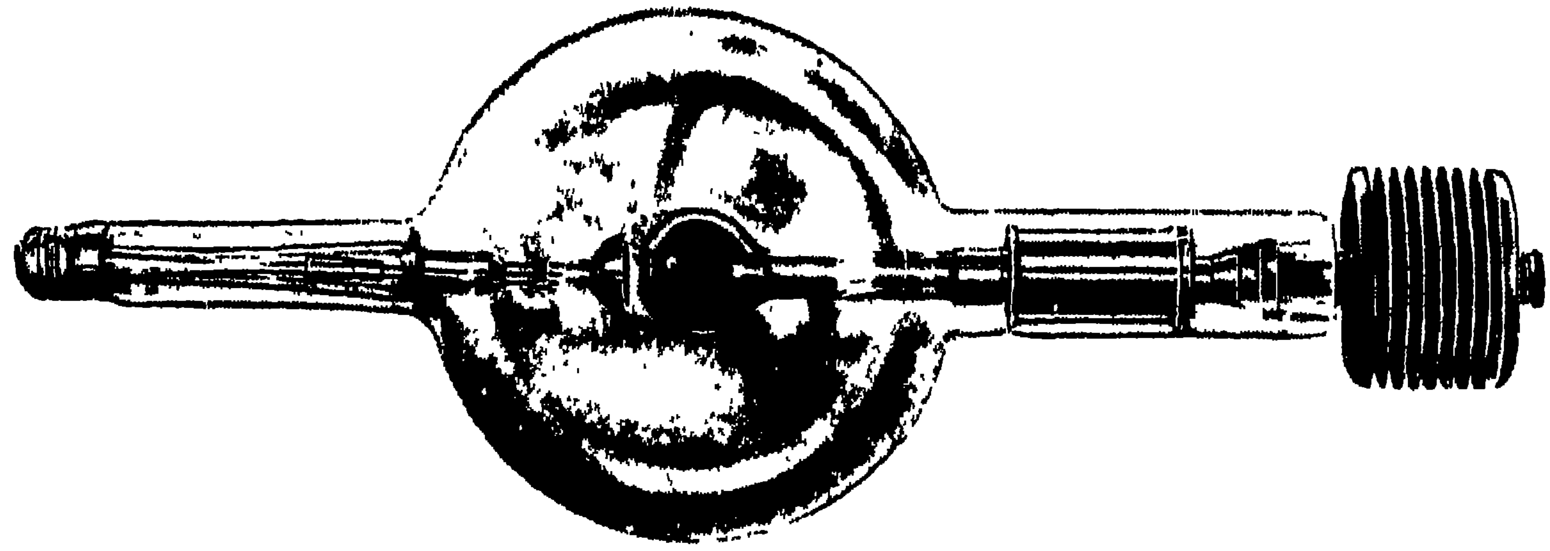


Fig. 532.—100 milliamperes Hooded Radiator Coolidge Tube.

[To face p. 533.

this company employs an external lead hood to intercept undesired non-focal radiation.

Recent developments in Coolidge tubes embody the more extended commercial production of the water-cooled deep therapy tube (p. 154). This (Fig. 531), by virtue of its forced water-cooling, is specified to pass 30 to 50 milliamperes at 200 to 250 kv. Its characteristic feature is the large disc-shaped anode, within which water is circulated. Its length is 40 in. and diameter 8 in.

The recessed anode of Fig. 84 has also been applied to a practical tube (Fig. 532) known as the " 100 milliampere radiator tube." The anode is surrounded by a large copper hood, which serves the dual purpose of absorbing non-focal radiation and conducting heat from the target. In consequence, the tube can work as a self-rectifying tube for 10 seconds at 100 milliamperes, or at 350 milliamperes for flash exposures (1/10 second).

The Victor Company give interesting details of the characteristics of all commercial Coolidge tubes as regards size of focal spot, permissible currents and voltages as under :—

| Kind of Tube. | Approx. dia. Focal Spot. | mA. | KV Peak. | Approx. In. Point Gap. | Time. |
|---|---|---|---|---|---|
| | in. | | | in. | |
| Therapy water-cooled | 1 | 50 | 250 | — | Continuous. |
| Therapy Air-Cooled | $\frac{15}{32}$ | 5 | 200 | 14 | Continuous. |
| Therapy air-cooled with blower | $\frac{15}{32}$ | 8 | 200 | 14 | Continuous. |
| Universal : | | | | | |
| Broad focus | $\frac{15}{32}$ | 5 | 140 | 10 | Continuous. |
| | | 80 | 100 | 6 | 5 seconds. |
| Medium focus | $\frac{23}{64}$ | 50 | 100 | 6 | 5 seconds. |
| Fine focus | $\frac{9}{32}$ | 25 | 100 | 6 | 10 seconds. |
| | | 100 | 100 | 6 | 1/10 second. |
| Radiator : | | | | | |
| 100 milliamperes | $\frac{13}{64}$ | 100 | 87 | 5 | 10 seconds. |
| | | 350 | 55 | $2\frac{1}{2}$ | 1/10 second. |
| 30 milliamperes | $\frac{11}{64}$ | 30 | 87 | 5 | 20 seconds. |
| | | 100 | 87 | 5 | 1/10 second. |
| 10 milliamperes | $\frac{1}{8}$ | 10 | 87 | 5 | 30 seconds. |
| Dental, right angle | $\frac{1}{8}$ | 10 | 63 | 3 | 60 seconds. |

It is remarkable that the attempt has not yet been made to obtain the effect of a line focus (p. 137) by modification of the anode, rather than, as proposed by Goetze, the more complex filament cathode. In a target hood, as the tube of Fig. 532, if the inlet to electrons facing the cathode were given a deep oblong form, the electrons, owing to the electrostatic repulsion of the negatively charged hood walls, would give an electron stream of oblong cross section, and hence a line focus upon the target. This line focus could be further increased by a slit outlet so that the beam of X-radiation, of linear section, would, in perspective, appear a point as with the Goetze method.

according to the demand of the secondary circuit. If the resistance in the secondary circuit is lowered then more current flows in the winding, so that the back e.m.f. opposing the flow in the primary circuit is reduced, and to maintain the necessary output more current also flows in this circuit. Similarly if the secondary circuit resistance is increased, less current flows in the secondary circuit, and correspondingly the primary circuit current falls.

The objection to the auto-transformer is that, should the secondary circuit be earthed then, the resistance being reduced to nearly zero, a large current only limited by the size of the magnetic core can flow. Should this contact be due to accidental contact by a person then this dangerously heavy current flows *viâ* this person, unlike in the case of a resistance control where, since the flow is governed largely by the ohmic relation $C = \frac{E}{R}$, then any decrease of R must cause a larger current flow, which is largely wasted in the resistance, since the energy expended by the resistance is given by $C^2R$. Hence a resistance has a "ballasting" action on a large excessive current flow, and in the event of accidental earthing the result is not so serious.

Similarly, should an X-ray tube suddenly soften, the resistance control tends to choke back an excessive current, so that the defect is not so rapidly developed. There is no such action with the auto-transformer control, and the tube very rapidly deteriorates.

A further disadvantage of the auto-transformer control is that, whilst the inductance is large the resistance is low, and the conditions for undesired oscillatory current production are present, whereas resistance, as in the resistance control, tends to damp out such oscillations.

This is doubtless the chief reason why Coolidge * has found tubes to work steadily upon resistance control, when they were too erratic to work upon auto-transformer control, since the erratic behaviour was doubtless due to high-frequency oscillations.

In spite of this there is a general tendency in German X-ray apparatus working with electronic valves and tubes to dispense with the resistance control in favour of a resistance control of an equal number of steps.

* *Amer. Jour. of Rönt.*, 9, p. 77, 1922.

Each unit (Fig. 534) develops by a transformer ($S_1$ to $S_4$) a voltage of 150 kv., which is rectified by valves ($K_1$ to $K_8$) charging pairs of condensers ($C_1$ to $C_8$), and giving a total voltage of 600 kv. across terminals E, or, allowing for losses, 500 kv. Spark lengths of 28 cm. between 50 cm. spheres have been obtained and of 1·2 metres between points. Outputs of 30 milliamperes at 500 kv. are produced, with a fluctuation below 5 per cent., so that the energy output is 15 kw. The production of 1,000 kv. by this method, which has advantages in some respects over high potential transformers, owing to absence of corona and high voltage dielectric variations, is foreshadowed by d'Arsonval.

In America, Mutscheller * has described a similar apparatus intended for deep therapy and capable of developing voltages of 300 kv. Switching arrangements allow a small current at high voltage to be obtained for therapy, or a heavy current at lower voltages for radiographic purposes. With the arrangement suggested, which is oil-immersed, the tension upon the valves is halved. A novel type of constant potential valve apparatus has been described by Brenzinger, Dessauer and Lorentz,† intended for diagnostic work with voltages varying from 25 to 225 kv., and so to overcome the necessity of reducing the full voltage by resistance in the more usual valve apparatus. This apparatus is built up of unit transformers of 8·85 r.m.s. kilovolts, unit multiple Leyden jar batteries of about 1,000 cm. capacity, and valves which are noticeable in having nickel anodes. The designers state that since, on puncture of condensers, tungsten anodes fuse, aluminium is equally suitable, whilst more easily worked and cheaper. Various combinations of the units are described to produce different potentials.

* *Amer. Jour. Rönt.*, 17, p. 328, 1927.
† *Jour. Rönt. Soc.*, 23, p. 184, 1927.

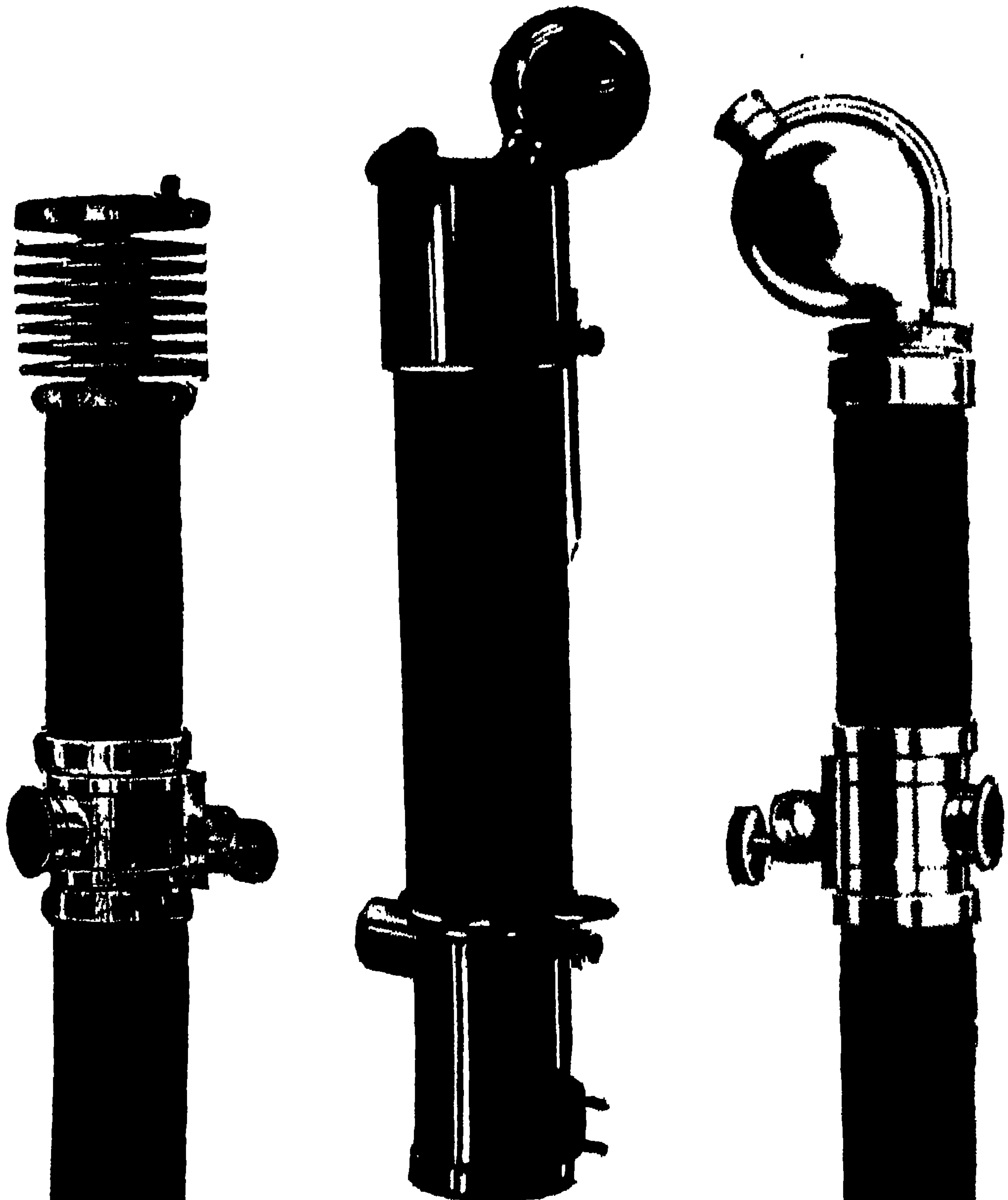
D.

PRINTED IN GREAT BRITAIN BY THE WHITEFRIARS PRESS, LTD.
LONDON AND TONBRIDGE.

# PHILIPS

# "METALIX" X-RAY TUBES

## In World-wide use.



Types "DNR" and "DSR."

Types "B" and "C."

Type "B" is fitted with our patented conically bored anti-cathode, which results in excellent definition.

Types "DN" and "DS."

**COMPLETE PROTECTION.** **WEIGHT ONLY 6 LBS.**

The tubes illustrated above are universally acknowledged to be the very finest for Radiography and Fluoroscopy. "METALIX" TUBES are also made for dental work and for deep therapy up to 200 K.V.

*OF ALL X-RAY DEALERS.*

**PHILIPS LAMPS LTD** Philips House, 145, Charing Cross Road, W.C. 2

*Telephone:* REGENT 7731. *Telegrams:* "PHILLAMPS, WESTCENT, LONDON."

*Branches:*

| | | | | |
|---|---|---|---|---|
| MANCHESTER | LIVERPOOL | BIRMINGHAM | LEEDS | GLASGOW |
| NEWCASTLE | CARDIFF | BRISTOL | NOTTINGHAM | BELFAST |